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Shallow Subsurface Drainage for Water Table and Salinity Control in the Magrath Irrigation District

by

© Dennis Rodney Bennett

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Shallow Subsurface Drainage for Water Table and Salinity Control in the Magrath Irrigation District" submitted by Dennis Rodney Bennett in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

A shallow subsurface grid drainage system near Magrath, Alberta was found to effectively maintain the water table at the depth of the drains (1.1 to 1.7 m). The water table rose to within 30 cm of the surface during irrigation periods and was effectively lowered to pre-irrigation levels within about 48 hours.

Soil salinity was decreased substantially only within the surface 30 cm. Soil salinity was not found to decrease with increased proximity to tile lines. Water quality of drainage effluent remained constant during the growing season with electrical conductivity ranging from 5 to 8 mmhos/cm and SAR from 7 to 10.

Crop yield was dramatically increased to 3900 kg/ha in 1978 as compared to 1310 kg/ha in 1977. This increase was mainly attributable to improved soil moisture and structure conditions at seeding time and to regular rainfall over the 1978 growing season. The decreased salinity of the surface 30 cm may also have accounted for improved moisture availability for crop growth.

The 30 m spacing of the tile lines was as effective as the 15 m spacing in providing water table control and decreasing the salinity of the root zone. Since the entire drainage system served as an interceptor or relief drain, a 60 m, or greater, spacing may have been equally effective.

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I. INTRODUCTION

Many agricultural areas in southern Alberta are threatened by the ever-increasing occurrence of waterlogged and/or saline soil conditions which significantly restrict productivity and lead to the annual removal of large acreages from normal crop production. The recent introduction of more economical subsurface drainage materials, coupled with the increased scarcity and higher value of cultivated land, has spawned increased interest in the use of subsurface drainage methods for water table control and reclamation of salt-affected areas.

In semi-arid and arid climates, drainage specialists have traditionally recommended that drains be installed at depths of at least two meters (U.S. Salinity Lab Staff, 1954; Thorne and Peterson, 1954; Gardner and Fireman, 1958; Talsma, 1963; Donnan and Houston, 1967; Luthin and Robinson, 1969; USDA-SCS, 1973; Donnan and Schwab, 1974) to control the rise of salt-containing water by capillary movement and the concentration of salts near the soil surface as the water is lost by evapotranspiration. It has been postulated (Van Schaik and Milne, 1962) that drains may be installed at depths as shallow as one meter in southern Alberta since lower evapotranspiration rates over a shorter growing season result in less upward movement of salts than in irrigated

regions of the United States and other countries.

A limited number of preliminary studies were undertaken in certain areas of southern Alberta, shortly after the introduction of subsurface drainage technology, to evaluate the efficiency and performance of conventional drainage materials within the relatively impermeable surficial geological materials which underlie most of the southern part of the province. Scientists therefore attempted to determine whether or not shallow subsurface drains would maintain the water table at a sufficient depth to provide adequate aeration and to curtail the accumulation of harmful levels of salts within the root zone under an intensive leaching regime. The more extensive installation of perforated corrugated plastic tubing in recent times, at relatively shallow depths, has prompted increased research toward verifying the theory that shallower drainage systems may be employed for adequate water table and salinity control in southern Alberta under normal cropping and irrigation practices.

The present study was undertaken to evaluate the ability of a shallow subsurface drainage system to control the water table and soil salinity for improved crop yields in an irrigated, saline lacustrine basin near Magrath, Alberta (NW 34-5-22-W4). The primary objectives of this study were to determine how well the drainage system provided water table control and to evaluate how the system modified the soil chemistry with reference to the

salinity-reclamation process. Objectives of secondary importance were to determine the impact of the system on crop growth and yield, to estimate the most effective depth and spacing of the drainage lines for achievement of the primary objectives, and finally, to extrapolate the findings to other areas of southern Alberta, inasmuch as this is possible.

II. LITERATURE REVIEW

A. Introduction

Drainage of agriculural land is a practice which dates back to the roots of civilization. The survival of many ancient peoples was dependent upon how well they were able to cope with the drainage problems associated with irrigated agriculture. Saline and waterlogged soils continue to plague mankind but drainage methods offer improved relief from these threatening and wasteful soil conditions.

Subsurface drainage has been defined as the removal of excess subsurface water by means of conduits or other water-conveying devices (Luthin, 1957). According to Van Schilfgaarde (1971), recorded examples of artificial drainage may be traced to the Roman Empire where open and simple covered drains were used in depressional areas around 200 B.C. The buried drains consisted mainly of stones laid in trenches which were subsequently backfilled. After the fall of the Romans, interest in drainage declined until its rediscovery in Europe during the eighteenth century. Subsurface drainage was introduced in the United States in 1835, and by 1850, increased efficiency of clay tile production, extrusion machines and horse-drawn trenching plows had made significant contributions to the drainage industry. With increasing mechanization, more economical

means of making tile, plus the development of flow theory which began with Darcy, rapid expansion of drainage practices continued. Probably the most significant recent advance in reducing the cost of drainage relates to the introduction of polyethylene plastics as pioneered by Schwab in the early 1950's.

By 1960 an estimated 92 million acres were drained in the United States (Van Schilfgaarde, 1971). A later estimate proposes that about one third (130 million acres) of all the cropland in the United States is drained artificially (USDA-SCS, 1973). These figures reflect both surface and subsurface drainage.

The purpose of such large investments in drainage practices has been described by Luthin (1973) as the provision of a root environment that is suitable for the maximum growth of plants such that production may be increased and yields sustained over long periods of time. Van Schilfgaarde (1974) specified that enhancement of agricultural use of the land may result from direct effects on crop growth, from improvement in the efficiency of farming operations or by establishment of a favorable salt regime. Wesseling and Van Wijk (1957) describe the objective of drainage operations as including the improvement of crop quality or soil conditions such that crops of higher value may be grown.

The need for drainage remains unquestionable. Reeve and Fireman (1967) estimate that the productivity of more than

one third of the 300 million acres of land which are currently irrigated, as well as millions of acres of potentially irrigable land, has been lowered due to salt problems. According to estimates by the United Nations and affiliated agencies, more than fifty percent of all irrigated lands of the world have been damaged by secondary salinization, alkalization and waterlogging (Food and Agricultural Organization, 1976).

Despite the apparent need for improved drainage, the adoption of drainage methods tends to fluctuate dramatically with the existing economic situation. In the past, farmers were persuaded by economics to abandon saline and waterlogged soils and to purchase new land rather than to take reclamation action. With increased value of agricultural land and the introduction of more economical drainage materials, attitudes have commenced to change, particularly in the irrigated areas of southern Alberta.

In order to evaluate the capacity of shallow subsurface drainage to meet the requirements of an effective drainage system, it is imperative that one has a thorough understanding of these requirements. With this basic knowledge one can assess the feasibility of such practices in the southern Alberta setting. The literature pertaining to the impact of shallow subsurface drainage on waterlogged and saline soils has been reviewed in the following section to achieve this understanding.

B. Drainage for Water Table Control

Knowledge of the factors affecting the growth of crops in soils under the influence of high water tables is a fundamental prerequisite to the amelioration of such adversely affected soils. Several workers have compiled comprehensive reviews discussing the impact of waterlogged conditions on crop growth and production (Russell, 1952; Van't Woudt and Hagan, 1957; Grable, 1966; Williamson and Kriz, 1970; and Wesseling, 1974).

The main repercussion of prolonged waterlogging of a soil is the reduction of soil aeration which results in direct adverse effects upon plant growth and metabolism, and equally important indirect effects upon other biological and chemical processes in the soil. Shallow subsurface drains must be able to remove excess water from the root zone in a time frame which prevents these adverse conditions from developing in a soil susceptible to waterlogging. The water table must be maintained at or below some critical depth determined by various soil, climatic and groundwater characteristics if crop production can be expected to be successful over prolonged periods.

Soil Aeration and Plant Growth

Adequate soil aeration is a requirement for normal water and nutrient absorption and for respiration by plant roots (Williamson, 1964). Suitable gas exchange is essential for maintaining an adequate supply of oxygen to the roots and for removal of carbon dioxide and other toxic substances.

Plants vary considerably in their response to inadequate aeration (Grable, 1966). The effects upon the plant as a whole are reflected in a reduction in root respiration and total root volume and increased resistance to transport of water and nutrients through the roots. Poor aeration over prolonged periods may lead to death of cells, decreased cell permeability, or even death of the roots with the amount of injury varying with the plant species, stage of development, soil and air temperatures and with the duration of waterlogging.

Plants are sometimes able to adapt to waterlogged conditions through the formation of new, specialized roots which have been described as thin and well-branched to provide a large absorbing surface. Deeper penetrating adventitious roots are formed by some species and such roots are characteristically thick due to the presence of large intercellular spaces (Van't Woudt and Hagan, 1957).

Excess Moisture and Soil Temperature

Of particular significance to the growth of crops is the relationship of moisture content to the thermal regime of the soil. A wet soil warms up slowly in the spring, retards seed germination and early seedling growth and usually results in poor stands and low crop yields. Even a slight increase in soil temperature contributed by improved drainage can significantly reduce the time required for emergence and thereby promote higher yields. As temperature of the soil increases, solubility of oxygen in water decreases, whereas respiration rate of plant roots and microorganisms increases (Williamson and Kriz, 1970; Hillel, 1971). Greater root injury may result at higher soil temperatures (under conditions of excess moisture) because more oxygen is required.

Some indirect effects of lower soil temperature on plant growth are evidenced by decreased mineralization of organic matter, decreased water uptake and reduced growth of roots (Wesseling, 1974).

Formation of Toxic Substances

Once the dissolved oxygen in a saturated soil has been depleted, anaerobic decomposition of organic matter and reduction of several mineral substances occur. Incompletely oxidized or reduced organic compounds such as methane, methyl compounds and certain complex aldehydes have been observed as the end products of anaerobiosis (Russell, 1952;

Van't Woudt and Hagan, 1957). Reduced forms of iron, manganese and sulfur also tend to accumulate to harmful levels in soils that are subject to prolonged waterlogging.

Other biochemical transformations may be altered in the absence of oxygen. Van Hoorn (1958) has described the major effect of proper drainage as the increased nitrogen supply from a deeper rooting zone. This effect is due to the resumption of nitrification, the oxidation of ammonium to nitrate by microorganisms; decreased denitrification losses; and an increase in the rate of decomposition of organic matter.

Concluding Remarks

Drainage serves to enhance adequate exchange of air between the atmosphere and the soil, contributes to the maintenance of an appropriate heat budget, prevents the accumulation of several toxic substances and promotes the mineralization of organic matter. In addition, decreased incidence of fungal root rots and other moisture-enhanced plant root diseases may be expected with proper drainage practices. Compaction of soil (caused by animal and machinery traffic) which accompanies high soil moisture content, can also be reduced when suitable drainage methods are employed (Reeve and Fausey, 1974). As a consequence of these and other improvements in the growth medium, crop production can be expected to be greatly enhanced by proper design and functioning of drainage systems.

C. Principles of Crop Growth in Saline Soils

Of particular relevance to the study of salinity control with shallow subsurface drainage is appraisal of the complex factors influencing the growth of agricultural crops in saline or sodic soils. Many well-known scientists have attempted to describe the adverse effects of excess soluble salts or high percentages of exchangeable sodium on the growth of plants and several efforts have been made to predict the salt tolerance of a variety of crops. A review of some of the important principles governing the growth of crops in salt-affected soils is presented below.

Origin of Soluble Salts

The origin of the commonly occurring salts found in soils are the primary minerals constituting the exposed rocks and soils of the earth's crust (U.S. Salinity Lab Staff, 1954; Fireman, 1957). These salts are slowly solubilized through physical and chemical weathering processes and are gradually added to surface and groundwaters which usually serve as direct sources of soluble salts (Reeve and Fireman, 1967). All natural waters contain quantities of dissolved salts, the concentration varying with the relative solubilities of the salts concerned and the nature of the soil and geological materials contacted by the water. The most common cations

promoting salinity in irrigated areas are sodium, calcium, magnesium, and sometimes potassium. Anions of significance are chloride, sulphate, carbonate and bicarbonate. Nitrate and boron also present a severe problem in certain areas.

Soil Salinization

Saline soils, as described in Handbook 60 (U.S. Salinity Lab Staff, 1954), are characteristically found in regions where an arid to semi-arid climate prevails. The development of well-integrated drainage systems in humid regions provides for the transportation of salts to streams and ultimately to the oceans. In arid areas, characterized by low rainfall and high evapotranspiration, movement of salts is not as complete since leaching is local in nature due to the inadequate development of natural drainage.

Where water tables are maintained at relatively high levels throughout part or most of the year, a significant capillary movement of salts in the groundwater to points nearer the soil surface can be expected. The rate at which water is transported towards the soil surface is governed by the capillary conductivity of the soil with respect to its moisture content and the potential gradient between groundwater and soil surface (International Institute for Land Reclamation and Improvement, 1972). The consumptive use of water by crops tends to increase the concentrations of the dissolved salts within the soil solution since the majority of the soluble salts remain behind in the soil

(Christiansen et al., 1977).

Leaching of salts with rainfall or good quality irrigation water is essential to the maintenance of a favorable salt balance within the root zone. Since restricted drainage often contributes to the development of high water tables, the provision of adequate drainage is fundamental to the reclamation of salt-affected soils and to the prevention of salinization of the root zone.

Measurement of Soil Salinity

The standard method for measuring soil salinity is determination of the electrical conductivity (EC) of the saturation extract of a sample taken from the root zone. The EC of a substance is the reciprocal of electrical resistivity where resistivity is the resistance in ohms of a one square centimeter conductor (Israelsen and Hansen, 1962). The EC measurements are easily performed and readily interpreted since they are proportional to the concentration of soluble salts in the soil solution. The saturation extract is employed because it is easily produced in the laboratory and can be used to estimate the salt content of the soil solution in the available moisture range. However, since plants are growing in a soil environment, it is often more meaningful to directly measure the salinity of the soil in the field moisture range. Two recently developed devices which may be used to determine the electrical conductivity of soil water in situ are salinity sensors and

four-electrode probes.

An important determination necessary for evaluating the sodium hazard is the sodium adsorption ratio (SAR) which is defined by:

$$SAR = \frac{Na^{+}}{\left[\frac{Ca^{++} + Mg^{++}}{2}\right]^{1/2}}$$

where concentrations are expressed in milliequivalents per liter. The presence of the sodium ion poses a potential problem when the exchangeable sodium percentage (ESP) is about 15 or greater. The detrimental effect is manifested by deterioration of the physical structure of the soil as clay colloids swell and disperse. Sodicity is particularly harmful in finer-textured soils having an abundance of expanding clay minerals. Although the amount of sodium in exchangeable form is the critical measurement, the SAR of the saturation extract is well correlated to the ESP and provides a much simpler means of surveying the sodium hazard. The criteria which are currently being used to classify a salinity or sodicity problem are presented below:

Table 1. Classification of salt-affected soils. *

Criteria	Normal	Saline	Saline-sodic	Sodic
EC (mmhos/cm)	< 4	> 4	> 4	< 4
SAR	< 13	< 13	> 13	> 13
pH	< 8.4	< 8.4	< 8.4	> 8.4

* James et al., 1977.

The time of sampling is another important point related to the diagnosis of saline soils. Graveland (1970) emphasizes that rapid changes in soluble salt concentrations

of the soil may occur throughout the growing season when water application and evapotranspiration are at a maximum. He recommends that samples be taken in the early spring or late fall when sampling is done to obtain a single value of salinity. This suggestion is corroborated by McMullin (1977).

Crop Salt Tolerance

The most obvious effects of salinity on crop growth are manifested by physiological drought and the existence of a patchy, irregular crop stand. Leaves may not only be stunted but sometimes exhibit a characteristic bluish-green color. The most serious effect is the resulting decrease in crop yields which has perplexed farmers for some time.

Many workers have attempted to describe the effects of excess soluble salts on the growth of plants. The effects of salinity on plant growth are usually separated into the osmotic effect and the specific ion effect.

The osmotic effect results from a decrease in the amount of water available to the plant caused by a decrease in the osmotic potential of a saline soil solution. Retardation of plant development is largely independent of the kinds of salts present (Hayward and Wadleigh, 1949). As the osmotic potential of the soil solution decreases, plant yield generally decreases.

The specific ion effect is attributed to an increase in the concentration of specific ions which have a

characteristic toxic effect on plant metabolism beyond the osmotic effect. These ions include chloride, sodium, boron, and in certain areas, lithium or selenium (U.S. Salinity Lab Staff, 1954). Carter (1977) has shown that ion ratios are also important in determining the effects of specific salts on plants.

Early reviews by Bernstein and Hayward (1958) and Bernstein (1964) and later ones by Ayers (1977) and Maas and Hoffman (1977) comprise early attempts to predict the salt tolerance of a variety of crops. The diversity of experimental procedures used in determining salt tolerance complicates evaluation of this important characteristic of plants. Crop salt tolerance is normally expressed as the expected decrease in yield for a given level of soluble salts as compared to yields on normal soils. Evaluation of crop tolerance data indicates that yields are generally not decreased appreciably until a threshold level of salinity is exceeded after which a linear decrease in yield is observed.

A number of factors are important in determining the tolerance of plants to salt. Plant factors include stage of growth and crop variety. Environmental factors such as temperature and relative humidity are also important. Soil fertility as well as the soil moisture regime are other significant factors altering the resistance of plants to certain levels of salts (ILRI, 1972).

Another point of controversy revolves around the soil criterion which should be used in assessing salt tolerance.

Many studies indicate that plants respond to the mean salinity of the root zone (Shalhevet and Bernstein, 1968; Maas and Hoffman, 1977). Bernstein and Francois (1973) concluded that yields are influenced to a greater degree by the zone of lowest salinity than by higher salinities elsewhere in the root zone. Eaton (1941) and Wadleigh et al. (1947) found that plant roots do not grow into zones of high salinity, the limits varying with a species ability to tolerate salts. Ayers (1977) and Maas and Hoffman (1977) explain that since water uptake is greater from the upper portions of the root zone, which is also most affected by leaching with irrigation water, the higher salinity of the lower root zone becomes of less significance to crop growth. Bernstein (1974) and Ingvalson et al. (1976) emphasized that yields are better correlated to time-integrated values of soil salinity than to mean EC's of saturation extracts (ECe) because salinity of the soil solution increases as water is lost through evapotranspiration. Whatever the criteria used, the plant integrates the several factors affecting water availability and responds to some weighted-mean salinity of the soil solution in the root zone. The need for drainage to provide a sufficient root zone and to allow for adequate leaching of salts appears to be evident from such studies.

Leaching Requirements

In order to ensure that the salinity of the soil solution in the root zone remains below the critical level, a downward flux of salt-laden water must be achieved by periodic leaching with good quality water. Leaching is defined as the process of dissolving and transporting soluble salts by the downward movement of water through the soil (Agriculture Canada, 1976). The leaching requirement is defined as the theoretical amount of leaching water needed to control salts in the root zone (FAO/UNESCO, 1973), or otherwise stated, as the proportion of irrigation water that must pass through the root zone to control soil salinity at any specified level:

$LR = Ddw/Diw = ECiw/ECdw$ (U.S. Salinity Lab Staff, 1954)

where Ddw and ECdw represent depth and salt concentration of drainage water and Diw, ECiw represent the irrigation water. Values for ECdw were based on the assumption that crops are responsive to the mean salinity of the root zone. Bernstein (1964) estimated ECdw as corresponding to an ECe value resulting in 50% yield reductions in field and forage crops. More recently Bernstein and Francois (1973) and Rhoades (1974) concluded that plants are relatively insensitive to high salinities in the lower portion of the root zone and LR's may be decreased to one-fourth of their previously calculated values.

Reduced leaching has also been encouraged in recent times to increase the water quality of return flows in

contrast to previous leaching which emphasized rapid removal of salts that resulted in higher salt loads of return flows. Shallow subsurface drainage requires more frequent applications of good quality irrigation water to maintain a downward flux of water and salts over time from the upper portion of the profile. Leaching is not 100% efficient. Leaching efficiency is defined as the hypothetical fraction of the water draining from the lower boundary of the root zone having the same salt concentration as the soil solution and ranging from 0.2 in fine-textured soils to 0.6 in coarse-textured ones (Bouwer, 1969). Bouwer also mentions that leaching efficiency not only depends on soil texture but on the irrigation method, rate and uniformity of water application, rooting depth of crop, and depth and spacing of tiles. With grid drainage systems a larger proportion of leaching water is expected to flow through the soil near drains as compared to the area between drains. Talsma (1967) showed that 74% of the salt was removed from the 60 cm soil depth near the tile lines, whereas only 20% was removed from the same depth midway between the tile lines. The tile spacing was 27 m and 30 cm of water were applied.

Dieleman (1963) states that water can be transported rapidly through the root zone by large pores and root channels, wormholes and cracks when they contact irrigation water at or near the surface. Bouma (1978) also emphasizes the importance of cracks. Nielsen and Biggar (1961-63) have promoted the concept that leaching efficiency increases with

the degree of soil unsaturation. They maintain that a certain portion of the porous matrix consists of non-conducting pores which have a tendency to retain the soil solution under saturated flow and release it as the finer pores begin to transmit water as the soil dries.

A study of the manner in which irrigation water moves through the soil profile is helpful in predicting the efficiency of any leaching regime in reclaiming a saline soil. The use of shallow subsurface drains allows a reduction in the distance dissolved salts must travel and therefore increases the rate reclamation may theoretically take place.

D. Subsurface Drainage Principles

Drainage Requirements

A number of investigations are necessary to determine the extent of a drainage problem. Of fundamental importance to any reconnaissance work is visual observation of the site itself and careful examination of any historical data related to the problem area. Subsequent technical studies are usually categorized as topographical surveys, soils investigations, and water table and water source evaluations. The topographical survey indicates the type of drainage system which feasibly can be employed and defines the suitability of an outlet. Soil investigations reveal the

nature of the various soil strata-their location, thickness and extent. Physical characteristics of the soil such as hydraulic conductivity are also essential and ranges are often estimated from the texture of the soil layers. Salinity and sodicity of the soil profile must be appraised also. Water table studies involving the use of water table wells and piezometers delineate the position and dynamics of the water table throughout the affected area.

Once the basic hydrogeological information has been assembled, a realistic estimate as to the drainage requirement may be formulated. The drainage requirement in humid regions is based on three conditions (USDA-SCS, 1973):

1. The maximum duration and frequency of surface ponding;
2. The maximum water table height;
3. The maximum rate at which the water table must be lowered.

In irrigated areas salinity control requires that drainage systems have the capacity to (Rhoades, 1974):

1. Handle the leaching requirement;
2. Control the water table at a minimum depth for prevention of upward movement of salts into the root zone.

These two sets of concepts must be integrated in the design of a suitable drainage system.

Drainage System Design

Over the past few years a great deal of experience has been gained in optimizing the design of drainage systems in many parts of the world. Much effort has been expended to develop a solid scientific foundation for the choice of depths and spacings of tile lines to satisfy a given drainage requirement. A great deal remains to be learned, however, since soil is a rather complex, heterogeneous medium requiring sustained and site-specific evaluation of its drainage characteristics. Schwab et al. (1966) describes the basic steps involved in planning a drainage system as:

1. Determine a drainage rate and water table height;
2. Estimate the hydraulic conductivity and other soil characteristics;
3. Select a suitable depth for the tile;
4. Compute the spacing.

These steps illustrate the importance of the preliminary investigations to the overall design of the system.

Depths and Spacings of Drains

The entire concept behind the use of artificial drainage materials for water table and salinity control, plus the economic feasibility of such a practice, revolves around the choice of drain depths and spacings for achievement of a suitable root zone for unimpaired crop growth.

Optimum Water Table Depths

In humid regions a great deal of research has been directed towards defining water table depths which provide adequate aeration in the root zone and yet allow crops to benefit from an underground water supply within their rooting depth. Optimum water table levels have been defined for a number of common agricultural crops (Williamsom and Kriz, 1970). Several challenges exist with respect to drainage design since different water table levels would be required for a particular crop as the growing season progressed. Such recommendations must also be modified according to existing soil characteristics, irrigation methods, climatological conditions and crop varieties (Wesseling, 1974).

Defining suitable water table depths for salt control is also desirable for any given set of conditions. Talsma (1963) states that no single-valued depth could be determined for salinity control in arid regions because such an estimate depends on soil physical properties, groundwater quality, crop characteristics and environmental conditions. Deeper water table control is generally needed for control of capillary rise under saline than under nonsaline conditions. Depths of two meters or greater are usually recommended (Talsma, 1963) for saline conditions. Soils of medium texture are most susceptible to upward movement of salts and may require greater depths for

water table control. Analysis of the several factors determining the flux of water and salt within the root zone must be undertaken to predict suitable water table depths for any specified region.

The height of the water table midway between drains is affected by the depth and spacing of the tile laterals. Kirkham (1949) concluded that the most influencial geometric factor affecting the rate of water movement from soil into drains is drain depth. Depth of drains is defined (Schwab et al., 1966) as the distance from ground surface to the bottom of the tile. Other factors of significance include the diameter of the drains, size of the perforations, spacing between laterals and the hydraulic conductivity and water potential distribution of the system. In discussing depths of tile lines it is important to realize that one is referring only to laterals since the depth of mainline is mainly determined by outlet suitability and topography (Schwab et al., 1966).

A number of principles must be remembered when recommending locations of tile lines. Drains should be oriented perpendicular to the direction of groundwater flow and within coarser textured deposits wherever practical (U.S. Salinity Lab Staff, 1954). Kirkham (1948) found that drains should not be placed too near, onto or into an impervious layer due to the ineffectiveness of the lower portion of the drain and

the resulting reduction in flow rate. Cavelaars (ILRI, 1972) mentions several restrictions to the choice of drain depths. These include the water level maintained in the collector ditch, the limitations of available drainage machinery and the occurrence of layers of less suitable permeability. Once a permissible depth of drains is chosen, a decision as to the optimum spacing to be used must be made.

Drain Spacing Theory and Formulae

Groundwater flow theory has become increasingly significant as drainage design continues to become more sophisticated over the years. Many drain-spacing formulae have been developed over the years which incorporate steady- and nonsteady-state flow theory to arrive at approximate solutions to drain-spacing problems. Due to the fact that simplifying assumptions are made in the derivations of the various equations, one must recognize these assumptions and use judgment in the application of flow theory to each field situation.

Steady-state flow theory is usually categorized into horizontal and radial flow theories. Horizontal flow theory is based upon the two primary assumptions of Dupuit-Forchheimer theory (Schwab et al., 1966; USDA-SCS, 1973):

1. That all streamlines in a gravity flow system are horizontal;
2. That the velocity along these streamlines is

proportional to the slope of the free-water surface, but independent of depth.

Horizontal flow theory is most applicable to humid regions having drains that are shallow compared to their spacing and where impermeable layers are located near the depth of the drains. Examples of commonly used drain-spacing formulae based upon an ellipse equation are Hooghoudt's equation for rainfall or irrigation water in equilibrium with the water table (Luthin, 1973), Kirkham's (1958) formula , and Donnan's tile-spacing formula (USDA-SCS, 1973). The major drawback of the ellipse equation pertains to negligence of the resistance caused by convergence of flow lines in the vicinity of the drains (USDA-SCS, 1973).

Radial flow theory is based on the assumptions that the water table is flat and the soil is homogeneous, isotropic and of infinite depth. Hooghoudt introduced an "equivalent depth" concept which combines hypotheses from horizontal and radial flow theories to eliminate the major limitation of the ellipse equation.

A number of drain-spacing equations based upon a steady-state condition have found wide application in humid areas, particularly those characterized by frequent, low intensity rainfall, but their application to irrigated areas is somewhat limited.

Several workers have developed drain-spacing formulae for areas typified by intermittent recharge

involving nonsteady-state flow theory. The most popular formula appears to be the one referred to as the U.S. Bureau of Reclamation formula which was derived by R.E. Glover and was developed for use by L.D. Dumm. (Van Schilfgaarde, 1974). This equation incorporates transient flow (falling water table) concepts which must be considered in an irrigated setting. Bouwer and Van Schilfgaarde (1963) have modified this equation to account for the differential rate of drawdown of the water table with distance from the drains. A complete description of these formulae is not included here since conditions at the Magrath research site, such as the heterogeneity of the soil, do not appear to be conducive to application of this classical theory. The principle drawback in applying most of these equations in southern Alberta is the difficulty experienced in obtaining representative values for soil parameters, especially hydraulic conductivity. Thus, a great deal of judgment and trial and error must be utilized despite the advances which have been made in flow theory.

E. Subsurface Drainage in Southern Alberta

Previous Research

Prior to the introduction of plastic corrugated tubing to southern Alberta for agricultural drainage purposes, a number of research projects were initiated by Agriculture Canada scientists to determine the feasibility and performance of conventional shallow subsurface drainage methods. The motivating hypothesis was that lower evapotranspiration rates, coupled with a shorter growing season in southern Alberta, would induce less upward movement of salts than in many other irrigated regions. These factors would allow shallower placement of drains on or above the glacial till, thereby greatly decreasing the cost of installation and allowing drainage in areas underlain by relatively impermeable material at shallow depths.

In accordance with this hypothesis, Van Schaik and Milne (1962) initiated a study in 1957 near Vauxhall, Alberta to evaluate the performance of shallow tile drains in reducing the electrical conductivity and sodium contents of a soil by intensive leaching. The soil was a Shallow Chin Loam which was characterized by coarse- to medium-textured material in the surface 0.7 to 1 m underlain by relatively impermeable glacial till. Clay tile drains were installed at a 75 cm depth and a 10 m spacing on small, rectangular plots

and leaching was carried out over a three year period with a total of 180 cm of water required to successfully reclaim the saline-sodic soil. Salt removal was concluded to be quite uniform throughout the plots since no trends with respect to proximity to tile lines were found. The formation of a nonsaline-sodic soil was not experienced as a result of the experiment. As with all experimental work under highly controlled conditions, caution must be exercised in extrapolating to field situations on a larger scale.

In a subsequent study (Van Schaik and Milne, 1963), an attempt was made to monitor the rate of salt accumulation in the root zone when the water table was controlled at a depth of 1 m on the same plots. Results indicated that continuous cropping contributed to a build-up of salts above the water table and pointed out the necessity of an adequate leaching program. In conjunction with this project, Laliberte (1962) studied the effect of spacings on water table recession and control. The rate of water table recession was found to decrease with increased tile drain spacing, as might be expected.

A few years later, Van Schaik and Stevenson (1967) tried to determine the minimum water table depth which could be allowed to prevent the accumulation of harmful levels of salts within the root zone. They postulated that water migration from shallow water tables during the winter could lead to net salt accumulation in the spring. This idea was later investigated by Van Schaik and Rapp (1970). They

concluded from this lysimeter study that a net annual upward movement of salt could be anticipated when the water table was maintained at less than a one meter depth. These results can be contrasted to those of Gardner and Fireman (1958) in the Western United States wherein lowering the water table from the surface to 60 to 90 cm was of little value in preventing salinization of the surface soil. One should recognize that these results are both site specific and extrapolation on a broad basis must be carefully undertaken.

Rapp (1968) conducted another study in the Vauxhall area to compare the effectiveness of lined and unlined mole drains to tile drains for water table and salinity control. The experiments consisted of the application of leaching water to a soil underlain by drains installed at a one meter depth. Waterlogging was successfully controlled with tile drains but the mole drains were found to be less effective. Soil reclamation was accomplished with all treatments but resalinization occurred on the plots underlain by mole drains when normal irrigation was resumed.

Sommerfeldt and Paziuk (1975) investigated a larger scale drainage system and monitored the water table and salinity changes under intensive leaching. Drains were installed at a 1.25 m depth and 25 m spacing. The water table was successfully controlled and the soil was reclaimed by the drainage system even to depths below the level of the drains (as explained by radial flow theory). When normal irrigation was resumed, however, there was evidence of slow

resalinization.

Maasland (Oldman River Study Management Committee, 1978) summarized the value of these pilot studies by drawing these conclusions:

1. Soil reclamation in southern Alberta is feasible with shallow tile drainage.
2. Permanent irrigation agriculture is feasible on these types of soils when drainage is employed.

He reiterated that subsurface drainage is the only method available for most of the irrigated areas of the Oldman River Basin, which permits removal of excess water in the soil profile to maintain a favorable salinity level in the root zone.

Current Drainage Practices

The installation of shallow subsurface grid drainage with plastic drain materials was introduced in southern Alberta about four years ago (1975). Prior to this time most of the drainage requirements were met by using large open surface drains or interceptor drains at depths from 2.4 to 3.6 meters. Paterson et al. (1977) have estimated that approximately 100,000 acres of the 900,000 to 1,000,000 acres of presently irrigated land in southern Alberta are affected to varying degrees by salinity and high water tables. A recent study estimated that 174,500 acres within irrigated and dryland areas from all the irrigation districts in the Oldman River Basin were adversely affected

by salinization (Oldman River Study Management Committee, 1978). The three major causes of this serious situation are (Paterson et al., 1977):

1. Seepage from canals and laterals from irrigation distribution systems;
2. Underground movement of excess water from higher recharge areas to discharge areas at some distance downslope;
3. Improper irrigation management.

The increased interest by farmers in shallow subsurface drainage may be illustrated by the amounts of plastic tubing installed in the past few years:

Table 2. Plastic drainage tubing installed in Southern Alberta.

Year	Quantity Installed
1975 *	45,000 m
1976 *	150,000 m
1977 *	300,000 m
1978 **	400,000 m

* Paterson et al., 1977.
** Paterson, B.A., personal communication.

The reasons for such rapid increases are related to some of the advantages of shallow subsurface drainage (Paterson et al., 1977):

1. Cost of tubing and installation are relatively low.
2. High speed trenchers and plows provide fast, accurate installation with minimum labor.
3. Coiled lengths of lightweight corrugated plastic tubing make handling easy.
4. Active reclamation takes place with each irrigation

while maintaining water table control within the area itself.

The rationale for using drains at less than two meter depths relates not only to the increased cost of installation with depth but also to the nature of the parent geological material of the area. The presence of relatively impermeable glacial till or lacustrine deposits at shallow depths, as found throughout much of the southern part of the province, makes application of much of the drainage design flow theory difficult.

The advent of plastic corrugated tubing to southern Alberta has fostered renewed interest in subsurface drainage and has stimulated experimentation to evaluate the performance of these drainage materials in the field setting. The site at Magrath is one of the sites being investigated.

III. MATERIALS AND METHODS

A. Site Description

Location

The site chosen for extensive study is located within the Magrath Irrigation District about 32 km south of Lethbridge, Alberta (NW 34-5-22-W4). The field in question is situated nearly 1.5 km northwest of the town of Magrath. The site lies near the bottom of a ridge which rises some 65 m higher to the west (Figure 1). Water from up slope moves downward through the coarser-textured layers and is forced upward where the sandy layers pinch out below the drainage site. Over time the salts have become concentrated within the root zone. A grid drainage system was installed in 1976 to improve the drainage of this 8.1 hectare tract of land moderately affected by salinity and a high water table. A certain portion of this study area, consisting of one 30 m drain spacing and two adjacent 15 m drain spacings, was chosen for intensive monitoring beginning in the spring of 1977.

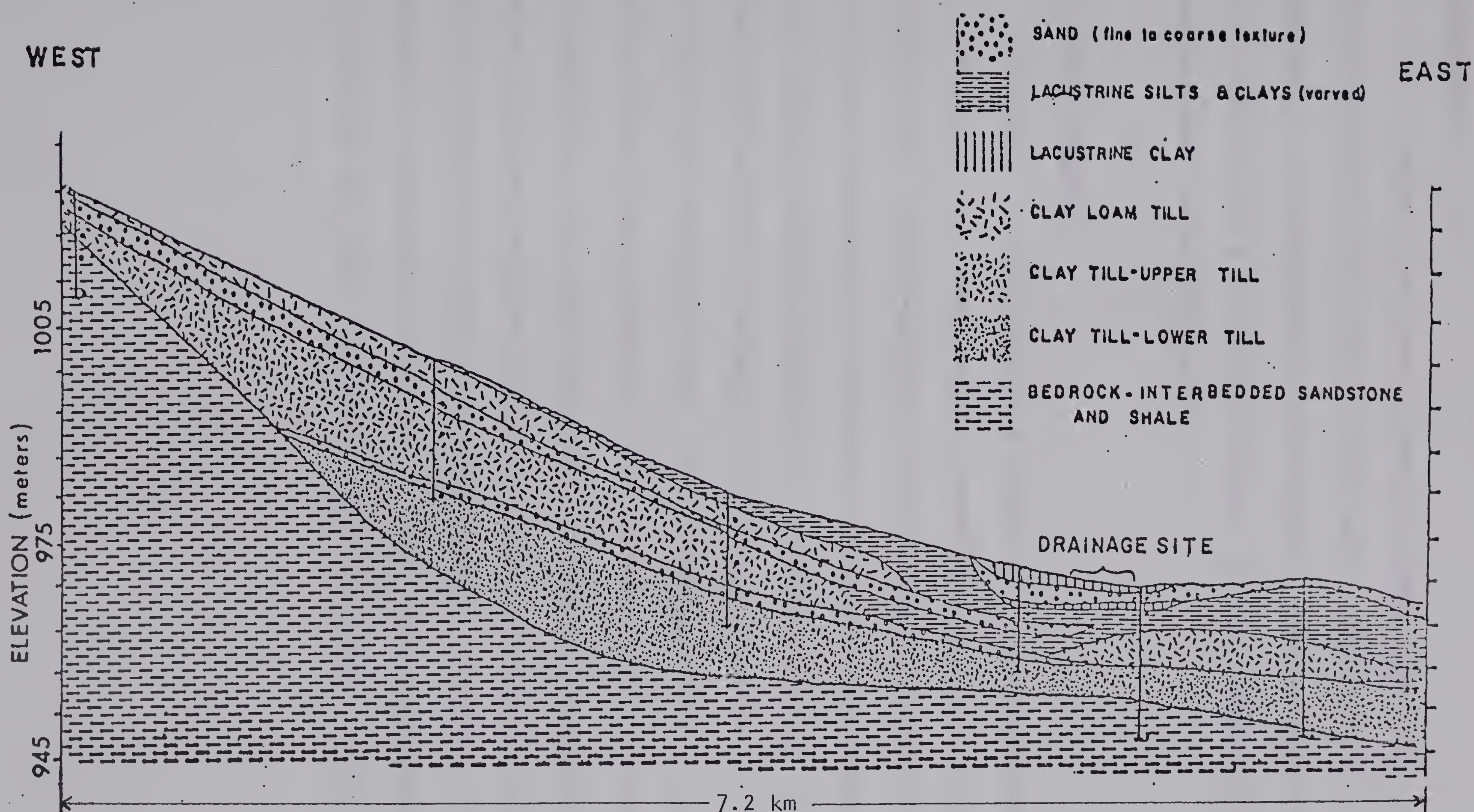


Figure 1. Geological cross-section of the Magrath area showing location of the drainage study.

Topography

The entire area has a gentle slope from west to east and northeast. The ridge to the west, slopes from a hilly to undulating topography in the western portion into a level to gently undulating lacustrine basin in the vicinity of the experimental site (Figure 1).

Bedrock Geology

Bedrock in southwestern Alberta is Upper Cretaceous in age and dips in a westerly to southwesterly direction in the Magrath area. Three bedrock formations are encountered in the area. The Bearpaw Formation consists of a light gray to buff, medium-grained sandstone of mainly marine origin. Where the cementing material is calcareous the rock is hard and resistant whereas clay, as a binding agent, results in softer rock. The uppermost beds mark a distinct contact with the overlying St. Mary Formation of softer sandstone and shale. A Blood Reserve formation of sandstone, overlying the Bearpaw Formation, has also been located near the site. Two preglacial channels belonging to the Whoop-up system also cut through the site (Vander Pluym and Kerr, 1971).

Surficial Geology

The lacustrine basin near Magrath consists mainly of alluvial and lacustrine materials originating from proglacial Lake Magrath which drained to the southeast along Verdigris Coulee. Several sand and gravel lenses were deposited within the lacustrine material near the surface. Horberg (1952) describes the Lower Till underlying the lacustrine deposits as being dense, clayey, pebbly and moderately columnar. A layer of intertill sand separates this deposit from the Basal Till which has been described as having prominent columnar structure, clayey composition, and a low pebble content (Vander Pluym and Kerr, 1971).

Soil Information

Analysis of saturation extracts of soil samples taken from the site in 1975 and 1976 (Table 3) yielded electrical conductivities ranging from 3 to 10 mmhos/cm and sodium adsorption ratios of 5 to 14. Generally, the highest concentration of salts was found in the surface samples.

Table 3. Soil chemistry of samples taken in the fall of 1975 and 1976 .

Depth (cm)	1975 EC	1975 SAR	Depth (cm)	1976 EC	1976 SAR	Depth (cm)	1975 EC	1975 SAR	Depth (cm)	1976 EC	1976 SAR
		Site A-7						Site A-9			
0-30	9.47	13.75	0- 15	9.5	13.42	0- 30	8.58	11.11	0- 30	8.1	10.36
60-90	8.05	11.96	-	-	-	60- 90	6.00	7.40	60- 90	6.3	8.09
-	-	-	-	-	-	150-180	6.75	9.64	120-150	6.3	7.33
		Site C-7						Site C-9			
0-30	5.50	7.31	0- 30	10.8	13.44	0- 30	4.74	7.16	0- 15	5.7	5.87
60-90	4.37	5.70	60- 90	3.7	5.34	60- 90	3.40	4.42	-	-	-
-	-	-	120-150	3.1	6.10	-	-	-	-	-	-
		Site E-7						Site E-9			
0-30	5.81	7.49	0- 15	8.1	8.36	0- 30	7.85	11.13	0- 30	7.7	8.73
60-90	5.57	7.25	-	-	-	60- 90	7.35	9.29	60- 90	7.3	11.24
-	-	-	-	-	-	120-150	5.16	6.41	120-150	6.6	9.06
		Site G-7						Site G-9			
0-30	8.51	11.91	0- 30	7.9	9.57	0- 30	3.99	3.91	0- 15	6.3	6.76
60-90	7.07	11.03	60- 90	7.7	10.25	60- 90	6.29	8.80	-	-	-
-	-	-	120-150	6.3	7.78	-	-	-	-	-	-

B. Installation of Grid Drainage System

Prior to installation of the grid drainage system, an extensive drilling program was carried out to characterize the surficial material into which the drainage system was to be installed. This information is presented in the results and discussion section of this thesis. A suitable grid drainage system was designed after completion of a detailed topographical survey of the site. Installation of the drainage tubing began in May of 1976 and continued for a ten day interval. A Barth ladder trencher equipped with a Laserplane grade control system was used throughout the installation procedures.

The system was installed according to recommended specifications of the Drainage Section (Figure 2). The mainline consisted of 150 mm plastic, perforated, corrugated tubing installed on a 0.2% slope at a depth of 1.7 to 1.8 m. The laterals consisted of 100 mm tubing installed at depths ranging from 1.1 m at the west to 1.7 m some 300 m to the east. Laterals number 2 through 10 were placed on a 0.3% grade whereas the others were on a 0.2% grade. All laterals were installed on a 15 m spacing with the exception of line 14 which was randomly omitted to provide a 30 m spacing. Backfilling was done with a grader and backhoe.

The trencher experienced great difficulty working below depths of 1.25 m where soils were sticky and adhered to machinery. Water under pressure was required to keep the

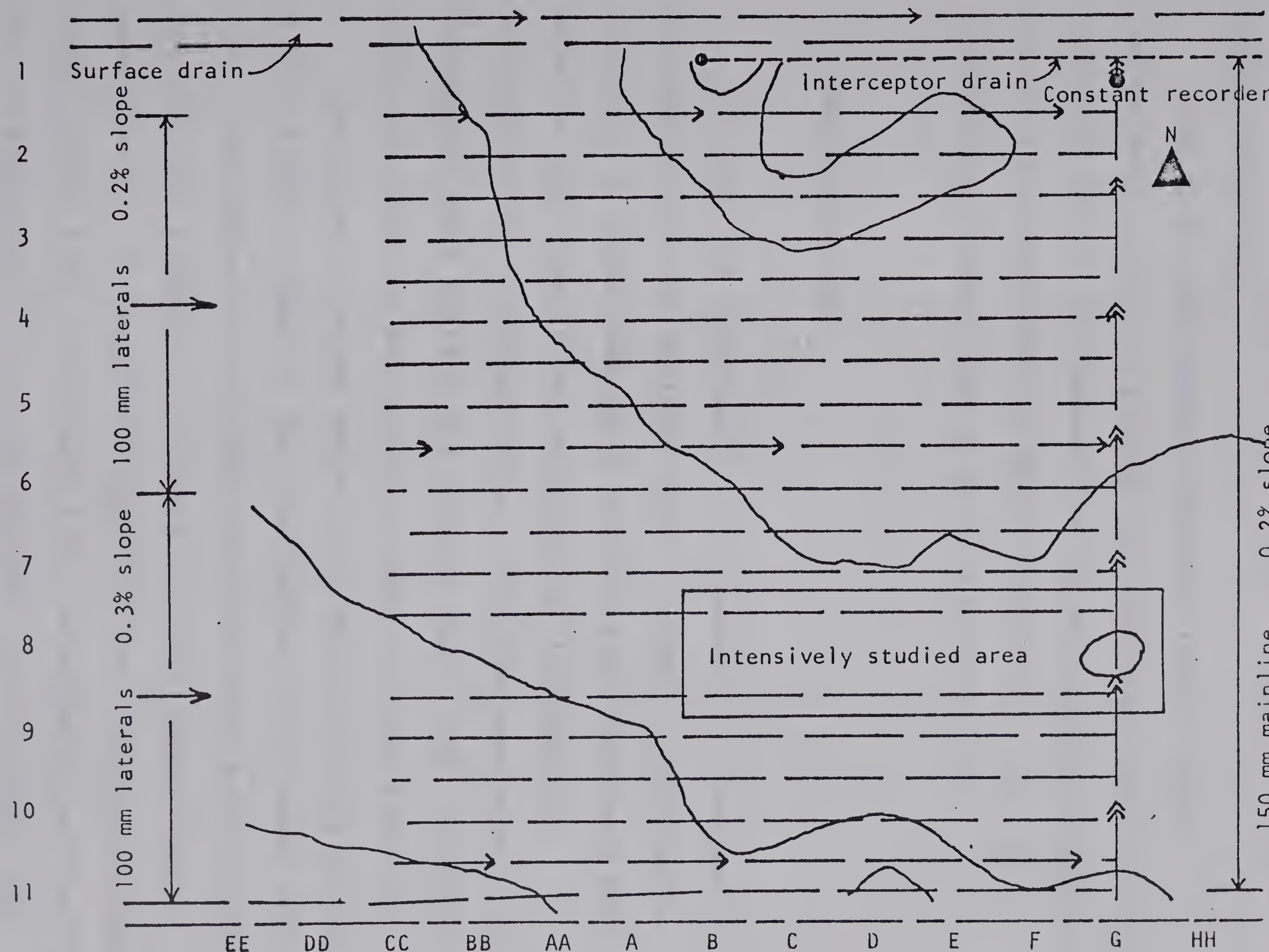


Figure 2. Design of the grid drainage system.

trencher operational under these circumstances. The machine functioned well when the saturated sand and gravel seams were encountered.

The whole grid system outletted into a buried interceptor (Figure 2), which had previously been installed parallel to the open Magrath Drain, to control sloughing of the banks. Flows from the outlet during the time of installation ranged from 0.75 to 2.4 liters/sec.

C. Instrumentation

A number of instruments were installed to evaluate the performance of the drainage system. Figure 3 depicts the location of these monitoring devices and reference should be made to this plan as the positions of the various instruments are outlined below. Grid reference points are designated with letters and numbers (i.e. E-8) and border dykes are shown as being east or west of these locations.

Ten lines of water table wells were installed in the border dykes to monitor the fluctuation of the water table and to determine the drawdown characteristics of the system following an irrigation or heavy rainfall. These wells consisted of 3 m lengths of slotted 38 mm diameter PVC pipe installed at 3.81 m intervals from the midpoints of the 15 m to the midpoints of the 30 m spacings on each dyke. The holes for placement of the wells were drilled with augers.

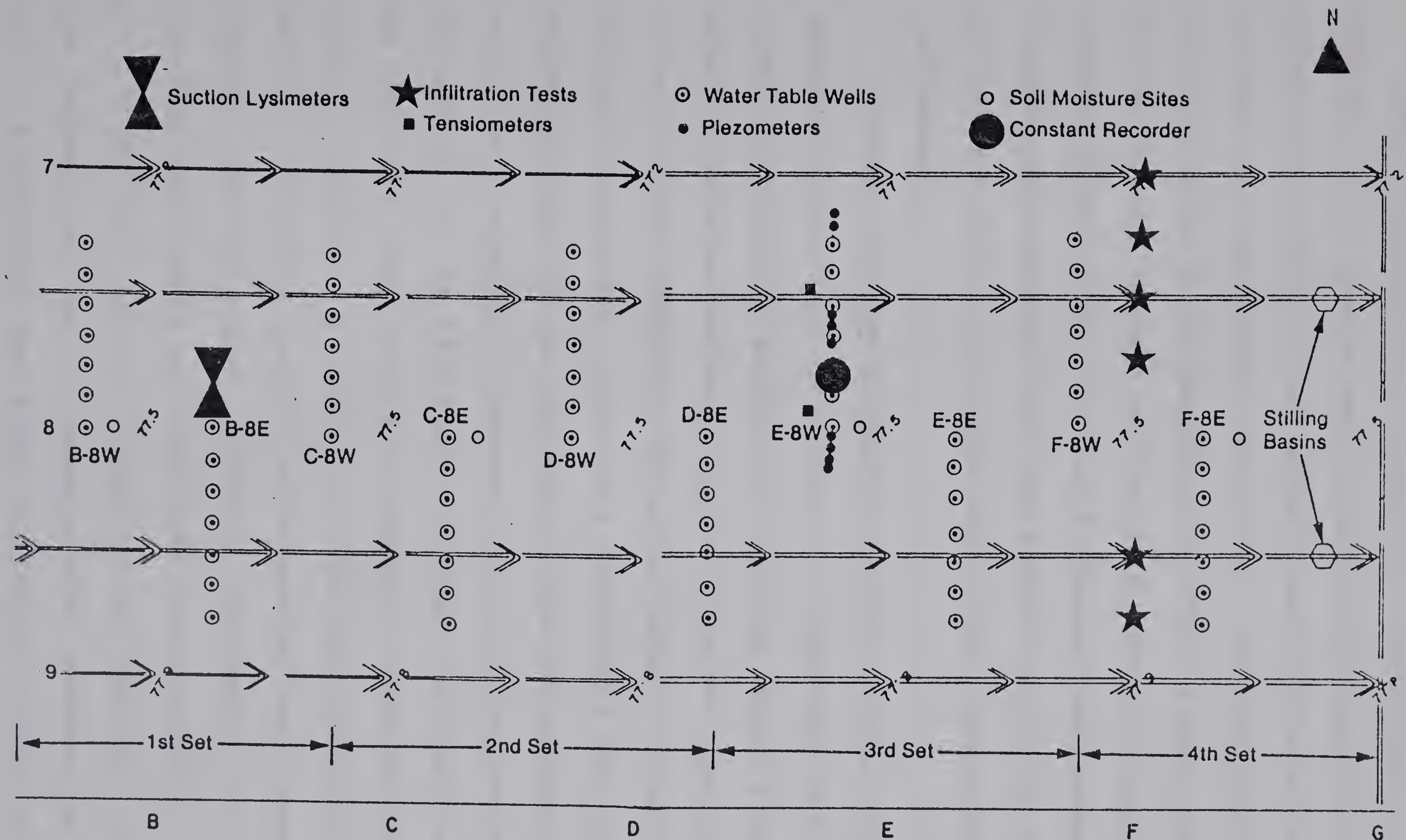


Figure 3. Location of instrumentation and sampling sites within area of intensive investigation.

Two tile lines and the mainline had stilling basins installed with them to monitor discharge volumes and to allow water samples to be taken. A constant water level recorder, in conjunction with a weir, was installed over the stilling basin on the mainline in 1977 to monitor changes in the volume of discharge at the outlet over the entire growing season (Figure 2). The following year another recorder was installed near the midpoint of the 30 m spacing on border E-8 West to monitor water table fluctuations continuously.

Several nests of piezometers were installed within and adjacent to the site to determine the direction and response time of groundwater movement through the assorted layers of material. Piezometers consisted of 50 mm PVC pipe to which a 46 cm filtered fibreglass tip was attached. Within the detailed study area 2 nests of 2 piezometers were installed which consisted of one tip placed below the gravel layer at a 3.75 to 4 m depth and another within the coarser material at 1.75 to 2 m. In 1978 three additional piezometers with 15 cm tips were placed within the material above the gravel layer at about a 1 m depth. All holes for piezometers were drilled with 100 mm augers. After setting the piezometers in position the holes were backfilled with coarse sand and then the tips were sealed off from above with bentonite.

A nest of 7 suction lysimeters was installed in one of the borders (B-8 East) to measure water movement and quality in the unsaturated zone during irrigation cycles. Holes were

drilled with a 50 mm auger and the ceramic tips of the lysimeters were placed at 15 cm intervals at depths from 0.3 to 1.25 m. A suction pump was used to collect water samples from the lysimeters.

Two nests of tensiometers were installed 1 m from the E-8 West border dyke at depths of 15, 30, 60 and 90 cm. The ceramic tips of the tensiometers were soaked overnight in distilled water prior to installation. An Oakfield sampler was used to excavate the holes into which the tensiometers were inserted. A slurry of soil and sufficient water to cover the ceramic tip of the tensiometers were poured into the holes before installation. Bentonite was placed around the tensiometer at the surface to prevent water movement down the side of the tube.

Syphon tubes (100 mm) were used to provide a given discharge for irrigation of the site by the conventional border dyke method. A V-notch weir was used in 1978 to determine the quantity of runoff water during the irrigation period.

D. Cropping

During the spring of 1977 considerable work was performed to prepare the test area for cropping. The area was levelled, land planed and border-dyked with borders being spaced at 15 m intervals. This extensive land forming caused a long delay in the seeding of the crop. Galt barley was finally seeded under very dry conditions on May 27 at 80 kg/ha. Prior to seeding, fertilizer was applied at a rate of 75 kg N, 60 kg P, 37 kg K and 45 kg S per hectare.

In 1978 extremely wet conditions hindered planting of the crop. On June 10, a crop of Galt barley was again seeded at the same rate as in 1977. Fertilizer had previously been applied at a rate of 80 kg N and 13 kg P per hectare.

E. Irrigation of the Site

Soil Moisture

Six sites were sampled in June 1977 at 15 cm intervals to a depth of 60 cm to determine the -1/3 bar and -15 bar moisture percentages for this soil. In 1978 four sites were sampled in a similar manner to 1 m to accomplish irrigation scheduling by the gravimetric method. An attempt was made to irrigate the site before 50% of available moisture had been used. Due to the uncertainty about the validity of the moisture retention numbers obtained, samples were gathered

in the fall of 1978 to have a check on the previous data. Gravimetric samples were also taken following irrigation to study the movement of water through the soil profile.

Water Application

The site was irrigated in four sets with three borders being included in each set. Three 100 mm syphons were required per border to supply a discharge of 34 liters/sec per border when a 15 cm head from the supply ditch was maintained. The length of each set was 6 hours for the second irrigation in 1977 (July 2,3) and was increased to 8 hours for the last two irrigations of that year (July 19,20; August 8,9). Water reached the end of the borders after 5 to 6 hours. Variability in head from the supply ditch necessitated changes in the duration of the sets. An estimated 400 to 600 m^3 of water were applied at each irrigation in 1977.

For the one irrigation in 1978 (August 1-3), some difficulty was experienced in obtaining sufficient water to maintain the 15 cm head in the supply ditch. Therefore, the length of sets was increased to approximately 12 hours to provide sufficient time for the water to reach the end of the borders.

The remainder of the field, a portion of which was underlain by the grid drainage system (Figure 2), was irrigated by the owner of the land. The adjacent field was cropped to volunteer barley in 1977 and Galt barley in 1978.

Precipitation and Evapotranspiration

Precipitation was measured with a rain gauge located immediately adjacent to the study area in the center of the field. Evapotranspiration and precipitation data, compiled by Alberta Agriculture, were collected using Gen atmometers and rain gauges at four locations within a 40 km radius of the study area.

F. Sampling Procedures

Soil Samples

Soil samples were gathered systematically in the spring and fall of 1977 and 1978 using 100 mm augers. Samples were taken 2 to 3 m to the east of each water table well. Samples were collected by 15 cm intervals to 1.20 m with another sample consisting of the next 30 cm interval to locate the concentration layer of salts in the soil profile. Twice during 1977 soil samples were taken to 60 cm at 15 cm intervals within 3 to 4 days following irrigation to determine any changes in salinity . These samples were obtained from alternate sampling sites along each border dyke (40 sites in total).

Water Samples

The quality of drainage effluent was determined by periodic sampling of the water at the outlet and from the 2 stilling basins on the individual tile lines. Samples from the outlet were taken by the vertical dip method whereas samples from the stilling basins were obtained with a bailer. Samples were collected on a weekly or bi-weekly basis throughout the growing season, with additional samples being taken during each irrigation cycle. Samples of irrigation water and surface runoff were also taken during the irrigation period. Groundwater quality was monitored by periodic bailing of samples from selected piezometers and water table wells. A portable YSI (Yellow Spring Instruments) electrical conductivity meter was used in 1978 to measure the concentration of salts in the groundwater in the field.

Water Table Levels

Water levels in the 70 water table wells and the piezometers were measured once or twice per week throughout the growing season and more intensively during irrigation periods. An electrical device for measuring water level was used for this purpose.

A constant recorder positioned over the stilling basin on the mainline provided continuous measurements of discharge from the grid drainage system over both growing seasons. Periodic measurements of water levels in the

stilling basins on the 2 individual tile lines also provided estimates of discharge from individual laterals.

Isotope Samples

Water samples bailed from shallow and deep piezometers and tile line stilling basins and collected from the drainage outlet, rain gauge and irrigation water supply ditch were analyzed for their oxygen-18, deuterium and tritium contents by the Isotope Lab, University of Waterloo, Waterloo, Ontario.

Crop Samples

Prior to harvest in mid-September of 1977 and 1978 square meter plant samples were obtained from selected locations adjacent to each of the 10 series of water table wells. Samples were harvested 3 m to the east of each water table well for a total of 70 samples per year. Samples were air dried for several weeks, then oven dried and threshed to obtain total dry weight and grain yield data. Stand counts were also taken each year when the crop was nearing the boot stage.

Hydraulic Conductivity and Infiltration Rate Tests

Ring infiltration tests were performed on 4 sites in June 1977 to estimate the capacity of the soil to accept applications of irrigation water. A constant head of water was maintained in the rings according to the method described by Bertrand (1965).

The hydraulic conductivity (K) of the soil was determined from semi-disturbed cores (Klute, 1965) taken to a 1.5 m depth for 6 sites within the drainage area. These analyses and bulk density and particle size analyses of the same samples were performed by the Soils Lab of the Irrigation Division, Alberta Agriculture, Lethbridge. Pump out response tests of the piezometers and water table wells within the study area were performed according to the method described by Hvorslev (1951) and included in Appendix 1. These tests reflect the permeability of the most permeable layer, in the case of water table wells, or the layer surrounding the tips of the piezometers.

Additional ring infiltration tests were carried out in the fall of 1978 to determine whether or not the backfilled material immediately over the drain was significantly more permeable than material elsewhere between the tile lines. Six sites were chosen for this supplemental study, three rings being placed right over the tile lines and three at the midpoints between the drains(between borders F-8 East and West). An attempt was made to obtain semi-disturbed cores from the same locations but the moist nature of the

material led to compaction of the cores and made sampling impractical.

In the fall of 1978 disturbed samples were taken to be analyzed in the lab according to Klute's (1965) method to permit comparison with the other results.

G. Methods of Analysis

Soil Samples

The electrical conductivity and SAR of soil samples were determined by the laboratory staff of the Soils Section of Alberta Agriculture, Lethbridge. Samples ground to 2 mm were used to obtain saturation extracts. Prior to filtration the saturated pastes were left overnight after which the pH was determined. A salt bridge was used to measure the electrical conductivity of the saturation extract. Sodium and potassium contents were determined with a flame photometer and combined calcium and magnesium by titration with EDTA. In 1978 calcium concentration was calculated by the difference between Ca + Mg by titration with EDTA minus Mg by atomic absorption.

Water Samples

Water samples were analyzed by the laboratory staff of the Water Quality Lab of Alberta Environment in Lethbridge. The water samples were analyzed for EC and SAR in a manner similar to the soil saturation extracts.

Other analyses were conducted to determine the concentrations of major anions in the water samples. The chloride concentration was determined potentiometrically using a titrimeter. The bicarbonate-carbonate content was also determined using a titrimeter and nitrate concentrations were determined colorimetrically using the disulfonic acid method. The sulfate concentration was estimated by calculating the difference between total cations and the sum of the other major anions as determined by the foregoing procedures.

IV. RESULTS AND DISCUSSION

A. Physical Characteristics of the Drainage Site

Of fundamental importance to understanding the response of a drainage system is a thorough investigation of the soil material surrounding the drains. Figure 4 indicates that the Magrath site is characterized by 90 to 120 cm of fine-textured (C to CL) material overlying a 30 to 60 cm layer of coarse sand and gravel which is underlain by fine-textured (SiC) lacustrine material. Deeper drilling in the area suggests that several coarse-textured layers are present at variable depths within the till. Bedrock below the test area is at approximately 21 m.

Installation of the tile lines within the coarser-textured layer in the profile is essential to the best performance of the drains. The fact that the coarser-textured layer is more or less continuous, but variable in depth and thickness, made proper placement of the drainage tubing somewhat difficult; nevertheless, overall installation of the system was close to the desired position. Results of several supplementary tests designed to characterize the nature of the soil material overlying the drains are outlined herein.

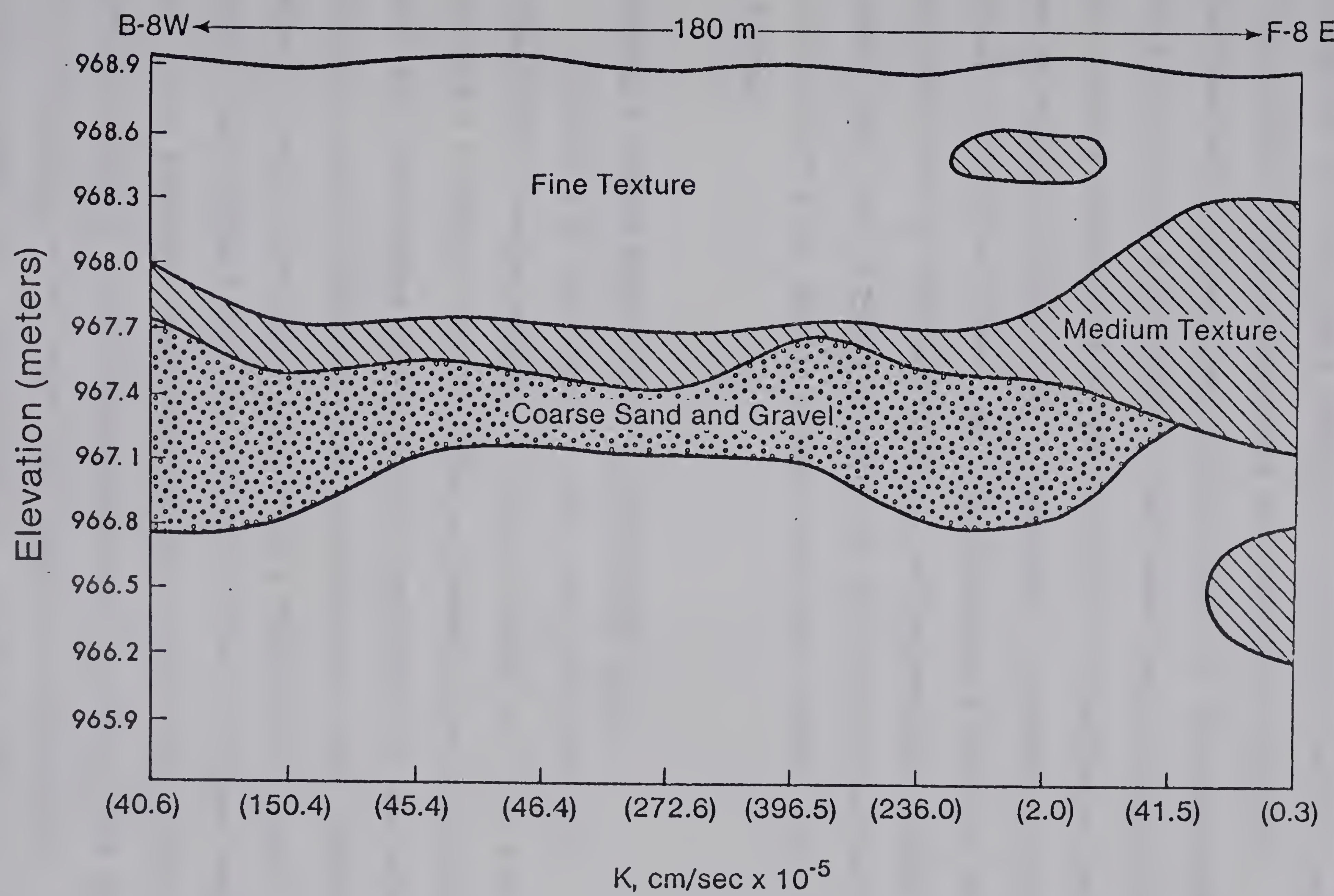


Figure 4. Cross-section of the area intensively monitored showing the variability in hydraulic conductivity of the most permeable layer.

Mineralogy

X-ray diffraction analysis of a surface sample indicated that the clay fraction was dominated by smectite clays (>50%). This proportion was estimated from an experimentally determined surface area of 465 m^2/g and a total CEC of 58.2 meq/100 g. The remainder of the minerals were mainly micas with lesser amounts of kaolinite and quartz present. These data correspond to results reported by Kodama and Brydon (1964) for the Canadian Prairies. Particle size analysis of several surface and subsurface samples showed that the texture of much of the study area was a clay to clay loam down to the coarse sand and gravel layer at a 1 m depth.

Hydraulic Conductivity and Infiltration Rates

Results for the infiltration rate and hydraulic conductivity tests performed in the spring of 1977 are outlined in Tables 4 and 5. The extremely low infiltration rates are surprising since a rapid response of the water table to applications of water was observed. The extreme degree to which the land surface was modified by land forming and grading operations just prior to these tests may have had a profound influence on the results obtained, however, similar observations were made later in the year when rings and ponded water were used to calibrate a salinity probe, i.e. infiltration was essentially nil. The data obtained for the semi-disturbed cores are also suspect

Table 4. Infiltration rates of selected sites within the drainage area - May, 1977 .

Grid Location	Infiltration Rate (cm/hr)
C-5	0.045
C-9	0.007
E-9	0.032
G-5	0.017

Table 5. Hydraulic conductivity (K) and bulk density (Db) of semi-disturbed cores taken from selected sites in May, 1977.

Depth (cm)	K (cm/hr)	Db (g/cm^3)	K (cm/hr)	Db (g/cm^3)	K (cm/hr)	Db (g/cm^3)
	Site A+25		Site G-5		Site G-3	
0- 15	0.128	1.48	0.07	1.53	0.096	1.48
15- 30	0.003	1.52	0.009	1.65	0.006	1.58
30- 45	0.003	1.52	0.006	1.56	0.001	1.68
45- 60	0.008	1.55	0.501	1.26	0.013	1.61
60- 75	0.008	1.55	0.047	1.44	0.002	1.83
75- 90	0.001	1.76	0.047	1.44	0.002	1.83
90-105	0.001	1.76	0.002	1.69	0.233	1.82
105-120	0.642	1.73	0.002	1.69	0.233	1.82
120-135	0.642	1.73	0.016	1.90	4.963	1.72
135-150	0.144	1.94	0.223	1.50	-	-
	Site E-9		Site C-7		Site C-5	
0- 15	0.001	1.50	0.003	1.56	0.001	1.45
15- 30	0.006	1.48	0.008	1.41	0.122	1.48
30- 45	0.001	1.65	0.023	1.48	0.004	1.63
45- 60	0.034	1.60	0.001	1.54	0.004	1.63
60- 75	0.008	1.61	0.001	1.54	0.063	1.65
75- 90	0.315	1.55	0.001	1.54	0.063	1.65
90-105	0.467	1.47	0.056	1.71	0.005	1.92
105-120	0.082	1.52	0.056	1.71	0.057	1.95
120-135	0.03	1.57	-	-	0.015	1.98
135-150	1.721	1.55	-	-	0.031	1.89

as illustrated by the extremely high bulk density (Db) values obtained for some cores. Similar results are reported by Ritchie et al. (1972) for a Houston black clay containing a high proportion of smectites. Compaction of some of the Magrath samples at sampling time was noted. This undoubtedly contributed to higher Db values. The texture and consistence of this soil material made use of this method somewhat questionable.

The pump out piezometer test results illustrate the extreme variability of the geological material within the coarser layer (Table 6). Comparison of representative K values for piezometers within (2 m piezometer) and below (4 m piezometer, 0.29 X 10^{-5} cm/sec) this coarse layer suggests that water movement into the underlying layer is negligible. Water movement within the coarse layer could be expected to be rapid throughout the area.

Infiltration test results from the fall of 1978 are similar to those obtained in 1977 (Table 7). No apparent difference was observed between results midway between the laterals and directly over the backfilled trenches, thus dispelling the hypothesis that rapid water table responses resulted from accelerated infiltration immediately over the tile lines.

Table 8 contains K values obtained from 3 sites as analyzed on disturbed samples in the laboratory. These numbers are substantially higher than those for the semi-disturbed cores but they also fail to explain the rapid

Table 6. Hydraulic conductivity of the coarser layer as determined by Hvorslev pump out tests on water table wells and piezometers.

Grid Location	K (cm/sec x 10^{-5})	Grid Location	K (cm/sec x 10^{-5})
F-8+75 E	8.1	D-8-50 W	311.5
F-8+50 E	11.2	D-8-75 W	58.2
F-8+25 E	4.2	C-8+75 E	124.6
F-8 East	0.3	C-8+50 E	138.5
F-8 West	41.5	C-8+25 E	41.0
F-8-25 W	75.8	C-8 East	36.4
F-8-50 W	0.6	C-8 West	45.4
F-8-75 W	3.8	C-8-25 W	140.7
E-8+75 E	0.4	C-8-50 W	36.3
E-8+50 E	8.1	C-8-75 W	25.6
E-8+25 E	8.1	B-8+75 E	18.8
E-8 East	2.0	B-8+50 E	348.9
E-8 West	236.0	B-8+25 E	87.2
E-8-25 W	48.5	B-8 East	150.4
E-8-50 W	127.5	B-8 West	40.6
E-8-75 W	48.5	B-8-25 W	33.6
D-8+75 E	207.7	B-8-50 W	101.4
D-8+50 E	27.7	B-8-75 W	43.2
D-8+25 E	581.5	1.5 m piezometer	15.6
D-8 East	396.5	2.0 m piezometer	231.9
D-8 West	272.6	4.0 m piezometer	0.29
D-8-25 W	25.3		

Table 7. Comparison of infiltration rates above the tile lines to positions midway between them - 1978 .

	Site Number	Infiltration Rate (cm/hr)
Over tile line:	1	0.0002
	3	0.0002
	5	0.001
At midpoints:	2	0.0004
	4	0.0014
	6	0.0017

Table 8. Hydraulic conductivity (K) of disturbed samples taken from selected infiltration rate sites - 1978 .

Depth (cm)	K (cm/hr)		
	Site #1	Site #2	Site #3
0- 30	0.03	0.02	0.04
30- 60	0.26	0.008	0.53
60-90	0.96	0.007	0.004
90-120	0.64	0.02	0.06

response of the water table during irrigation or heavy rainfall periods.

Moisture Retention Characteristics

The moisture retention parameters defining the available moisture range in this soil are tabulated for the four sampling sites (Table 9).

Table 9. Average -1/3 and -15 bar percentages of soil samples from the 4 sites used for irrigation scheduling.

Depth (cm)	-1/3 bar %	-15 bar %
0 - 30	37	20
30 - 60	31	18
60 - 90	30	16

The main purpose in gravimetric sampling over the growing season was for irrigation scheduling. The unusual response of the water table, however, warranted an appraisal of the soil moisture status as a supplement to other information acquired to gain a better understanding of the response in question. These data are included in Appendix 2.

Precipitation and Evapotranspiration Data

The precipitation data for the drainage site and the precipitation and evapotranspiration data for four surrounding locations are presented in Tables 10 and 11. The most significant observation to be made about these data is that 1977 was an extremely dry year whereas 1978 was an extremely wet one. This assumes particular significance when

Table 10. Cumulative precipitation (P, mm) and evapotranspiration (ET, mm) data from four locations near research site for 1977 and 1978 growing seasons.

		May	June	July	August
		Lethbridge Research Station			
1977	P	23.1	55.9	67.3	121.9
	ET	69.1	248.7	404.6	485.6
1978	P	95.5	114.3	204.7	373.9
	ET	66.3	177.8	338.6	454.4
		Del Bonita (NW 5-2-21-4)			
1977	P	23.4	63.8	74.2	156.2
	ET	27.7	150.4	282.4	355.3
1978	P	62.5*	92.7	179.3	313.2
	ET	16.8*	101.8	179.6	268.7
		Wilson Siding (NW 32-7-20-4)			
1977	P	33.0	84.8	96.8	186.9
	ET	44.4	179.6	313.7	376.7
1978	P	68.1**	90.2	227.3	368.8
	ET	22.1**	104.6	201.7	292.1
		Standoff/Glenwood (NW 5-5-26-4)			
1977	P	37.3	58.9	79.8	151.1
	ET	42.2	172.0	317.2	376.2
1978	P	57.4	69.6	197.6	295.9
	ET	27.9	123.4	215.9	292.6

* May 18 - May 31. ** May 16 - May 31.

Table 11. Cumulative precipitation (mm) from research site for 1977 and 1978 growing seasons.

	May	June	July	August	September
			Magrath (NW 34-5-22-4)		
1977	0*	27.7	47.8	102.4	119.1
1978	69.6	109.5	218.9	358.1	448.3

* May 25 - May 31.

considering the response of the barley crop to the extremes of climate. Long term average precipitation for this part of southern Alberta is reported by Longley (1972) as being 267 mm from May 1 to mid-September.

B. Evaluation of Water Table Control by the Grid Drainage System

The ability of the drainage system to control the water table was evaluated by referring to hydrographs depicting water table and discharge fluctuations throughout the course of the study. Piezometer hydrographs and water table recession curves were also prepared to aid in assessing the capacity of this system to maintain the water table at acceptable depths.

Water Table Fluctuations

The change in water level following installation of this grid drainage system is presented in Figure 5. Water level measurements indicated that the water table was lowered to depths corresponding to the locations of the tile lines within the drained area. Water levels remained high outside the area as shown by the converging contour lines. Similar measurements for a very wet year (1978) indicated that the water table was maintained at the depth of the drains only within the drained area. Groundwater was found to have EC values in the order of 3 to 9 mmhos/cm with SAR

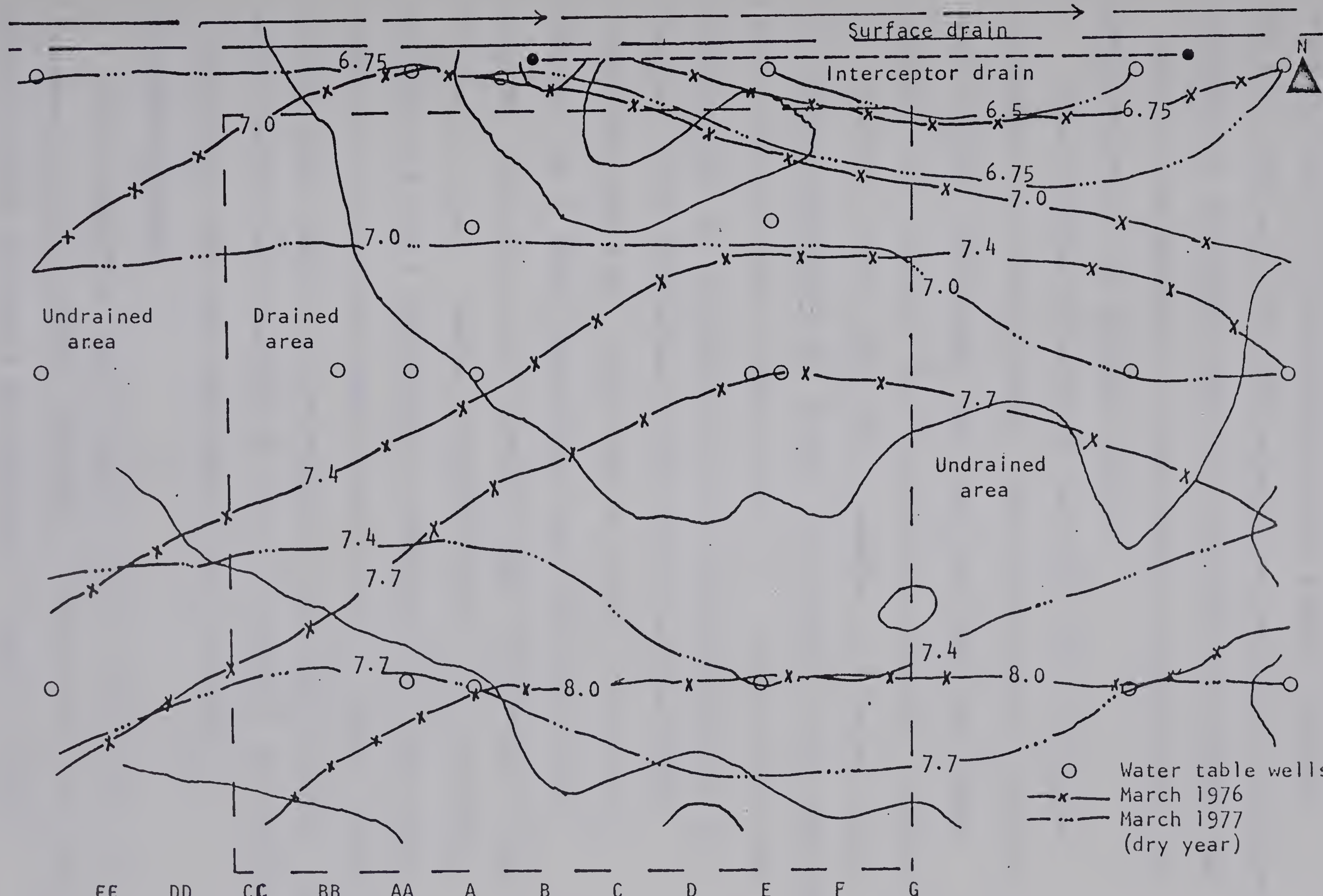


Figure 5. Water table contours before (1976) and 1 year after drainage (1977).

values from 5 to 9. Irrigation water was of excellent quality with an EC of 0.27 mmhos/cm and an SAR of 0.28. The response of the water table to irrigation and rainfall was therefore the question of prime concern in appraising the performance of the drainage system.

The response patterns of the water table during an irrigation and heavy rainfall (85 mm) are shown in Figures 6 and 7. These hydrographs were obtained from water level measurements acquired with the constant recorder situated on the E-8 West border dyke. This recorder is located within the third irrigation set (Figure 2). Figure 6 shows that the water table started to rise within 3 to 4 hours after the commencement of irrigation but the maximum level was not reached until irrigation of the fourth set was almost completed. The water table rose to within 30 cm of the surface for a short time, after which the water table receded gradually to its pre-irrigation level within about 48 hours. Figure 7 shows a similar curve for a presumably uniform and rapid application of precipitation. The steep slope of the ascending portion may be due to rapid response of the water table once the coarser layer became filled. The water table rose to within 25 cm of the surface and receded gradually in the same time frame as the curve for an irrigation cycle.

The relatively rapid response of the water table, as measured at the recorder following initiation of irrigation, may be better explained by referring to Figure 8 which

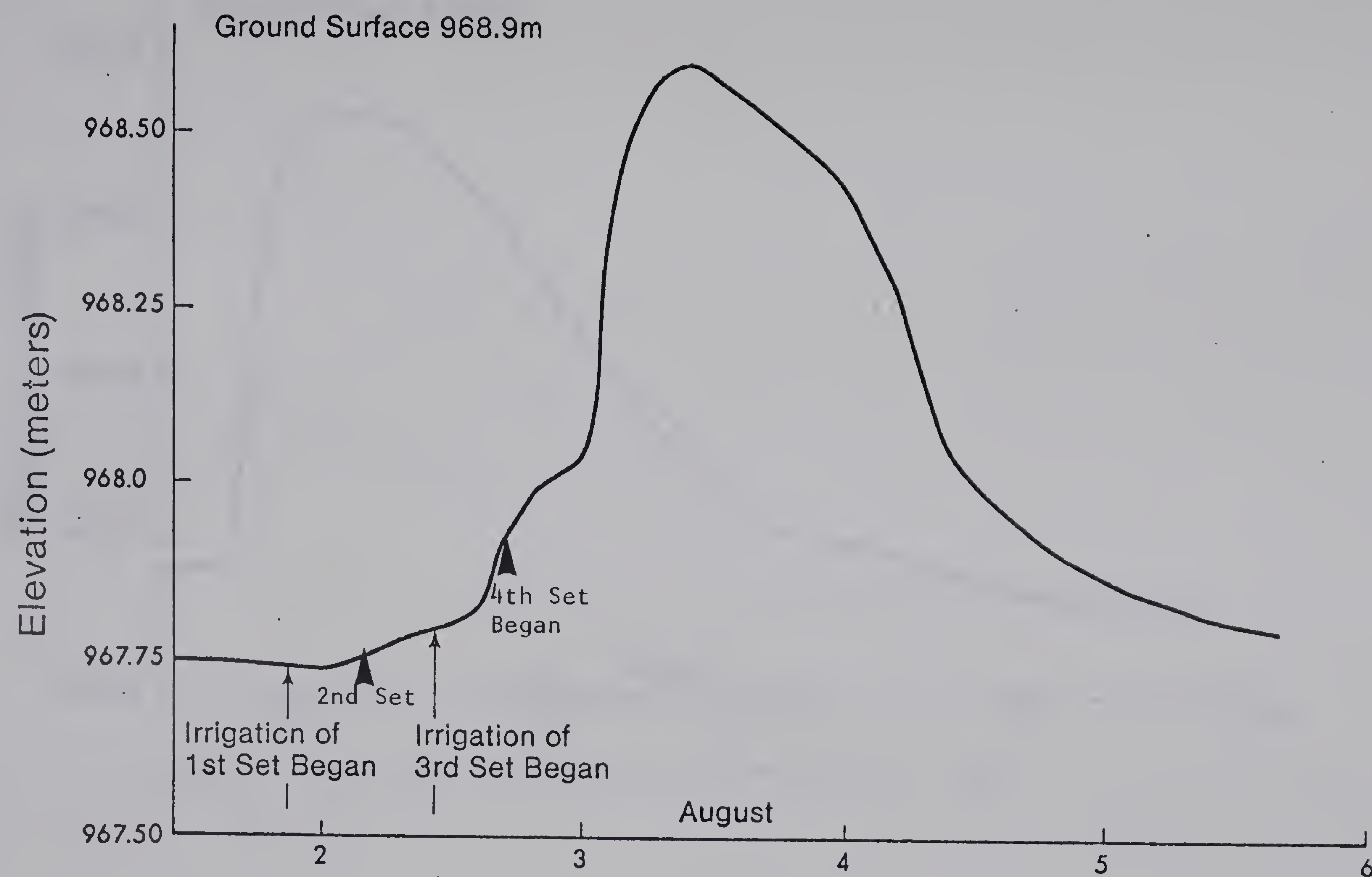


Figure 6. Water table hydrograph for first irrigation - 1978.

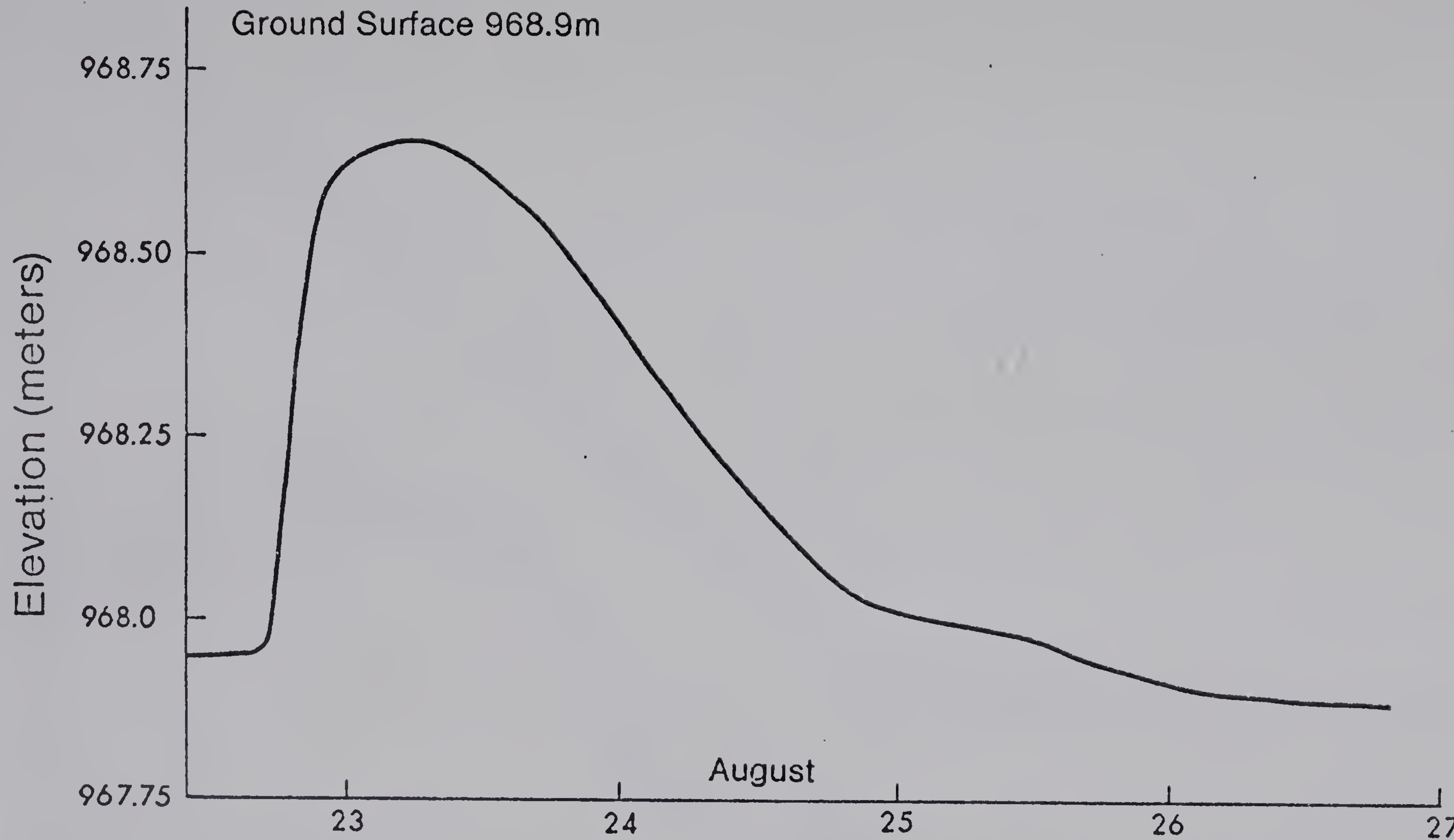
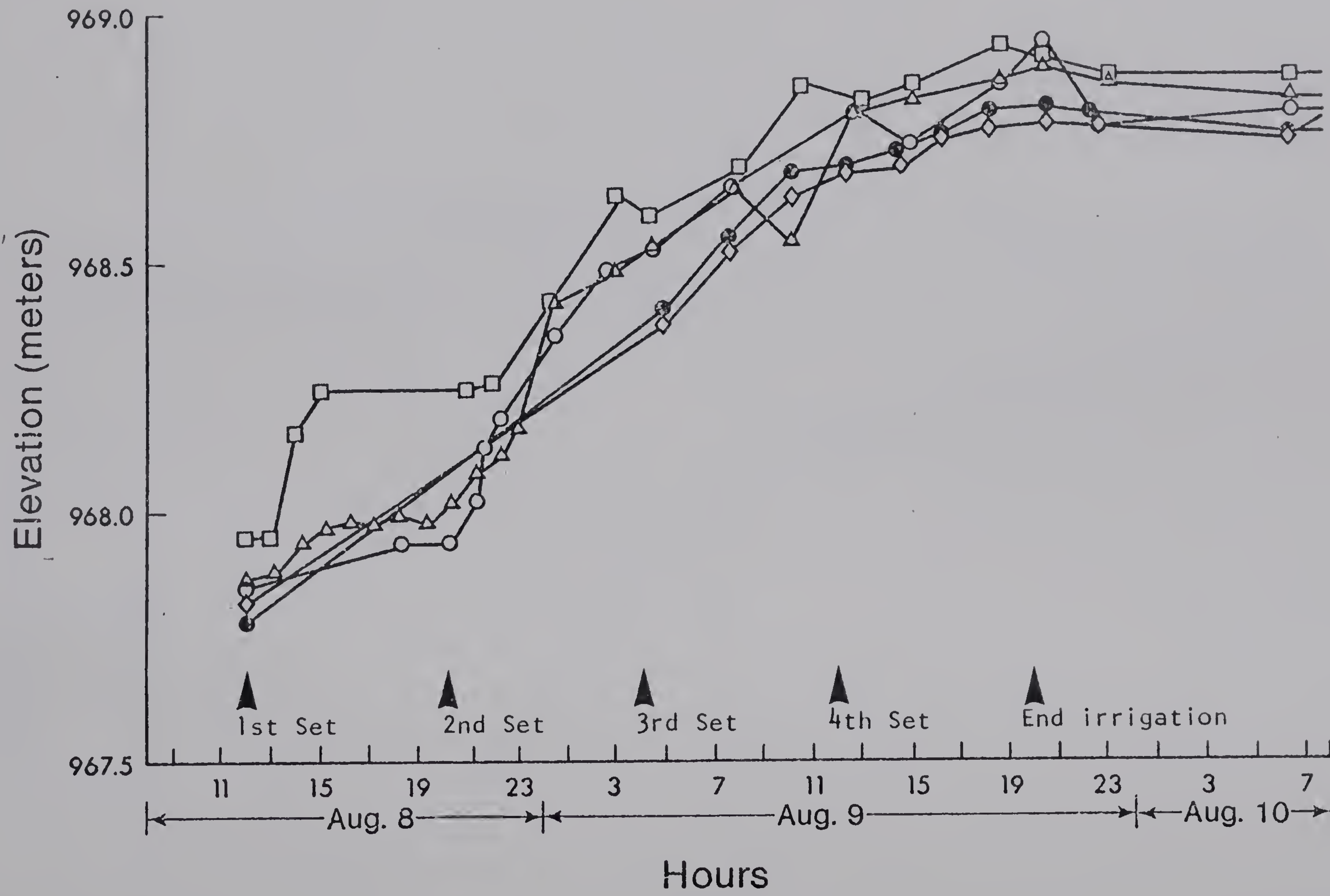


Figure 7. Water table hydrograph for 85 mm rainfall - 1978.


Elevation (meters)
969.0
968.5
968.0
967.5
1st Set
2nd Set
3rd Set
4th Set
End irrigation
11
15
19
23
3
7
11
15
19
23
3
7
Aug. 8
Aug. 9
Aug. 10
Hours

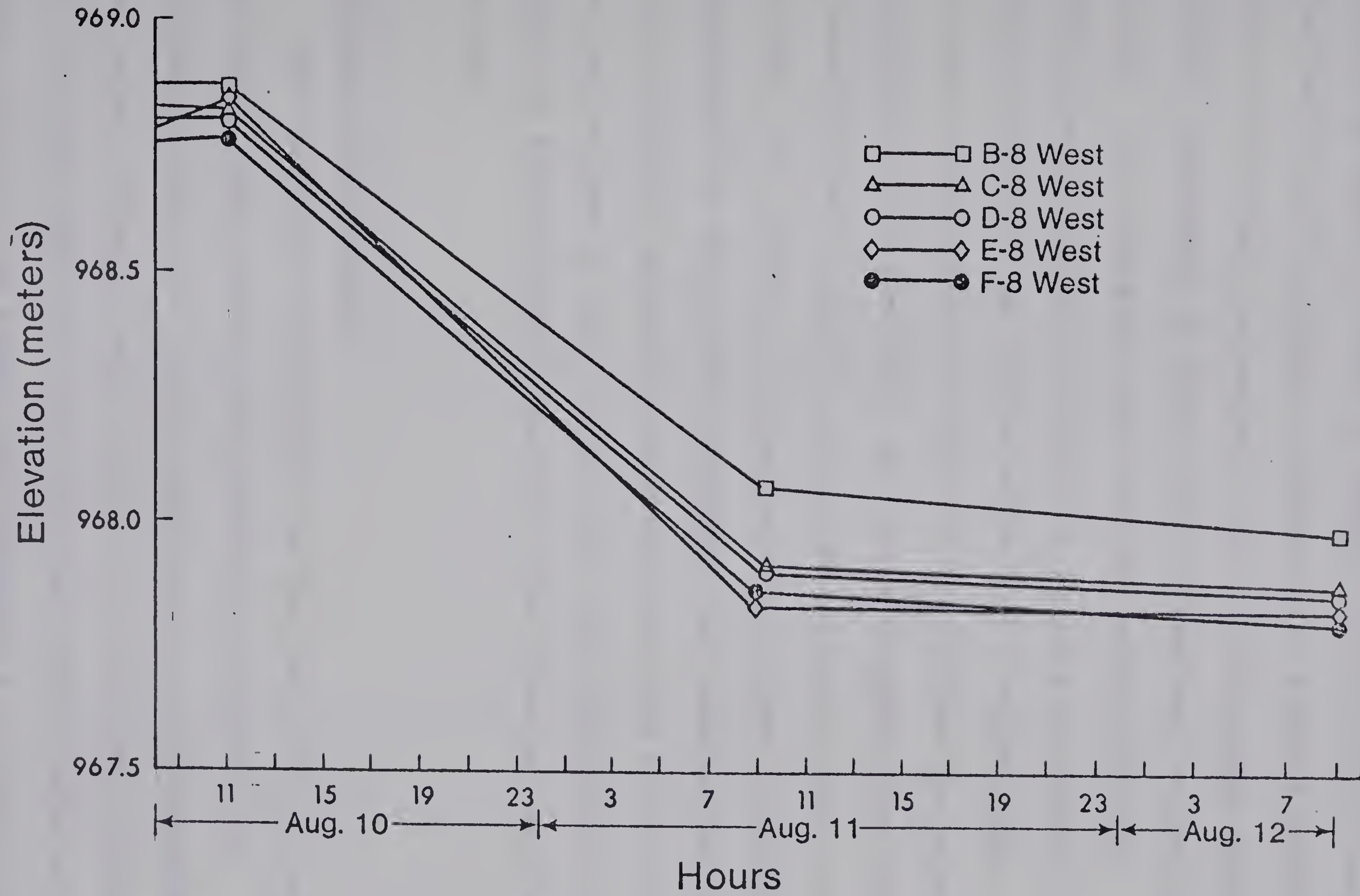


Figure 8. Water table hydrographs for fourth irrigation (1977) showing lag of the water table during the four irrigation sets.

illustrates the lag of the water table during the four irrigation sets (Figure 2) for the last 1977 irrigation. Irrigation began at noon on August 8 and each set had an 8 hour duration. The farmer irrigated his hay and seeded barley to the west on August 6 and 7. The points which are plotted correspond to water table elevations as determined over the tile lines on the 5 borders selected. This hydrograph is similar to Figure 6 in that the water table rose to within 30 cm of the surface and receded well within 48 hours. Soon after the start of irrigation the water table responded within the third set which suggests that water is transmitted very rapidly within the coarser layer throughout the site. The previous irrigation of adjacent crops likely contributed to this rapid response. The observation that the water elevation generally decreases from B-8 West to F-8 West may be due in part to the fact that the ground surface slopes in that direction and the tile lines are shallower in the west.

Discharge Hydrographs

The discharge hydrographs for the north tile line over both irrigation seasons are depicted in Figure 9 as determined from water level measurements and conversion to flow using a V-notch weir formula. The discharge hydrographs for the south tile line parallel these hydrographs so closely that it was deemed not necessary to include them both. The major fluctuations in flow in 1977 correspond to

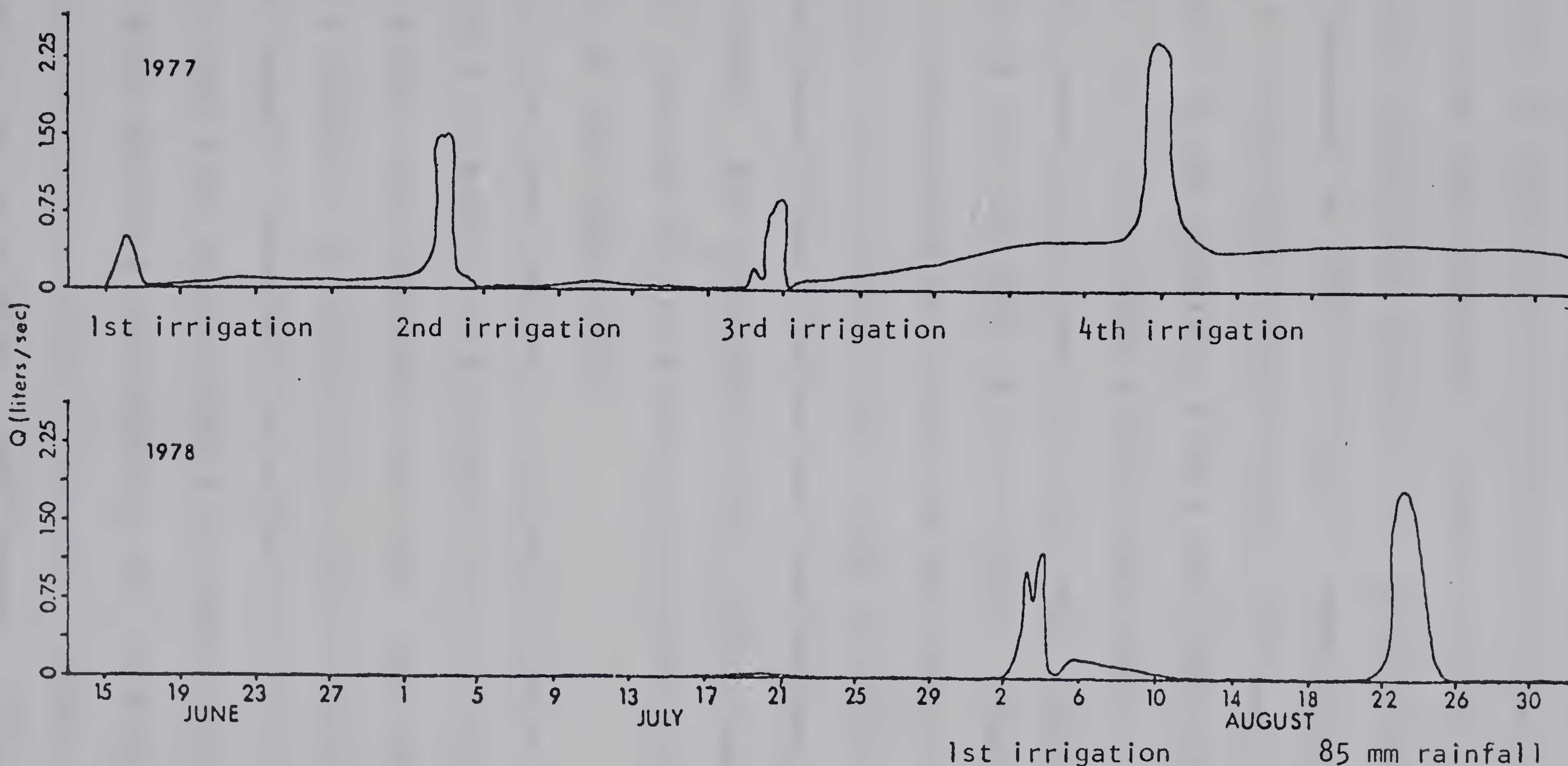


Figure 9. Discharge from the north tile line over both irrigation seasons.

the four irrigations which took place. The peaks in 1978 represent responses to irrigation of the site (August 1 to 3) followed by the farmer's irrigation to the west (August 6 to 10) and the high rainfall (August 22 to 25). Another significant observation involves the minimum flow rates for 1977 as compared to 1978. As already mentioned, 1977 was an extremely dry growing season whereas 1978 was extremely wet. The anomaly in the results is that low flow rates were maintained in 1977 between irrigations whereas minimum flow rates were essentially zero in 1978. This phenomenon may be explained by the lag time of the regional groundwater system, as influenced by irrigation up slope. The time frame required for water to move down slope towards the site would have to be investigated before any conclusions could be made on this matter. The sharpness of the peaks also illustrates the rapid response of the system during ascension and recession of the water table.

Discharge from the entire drainage system during major applications of water are depicted in Figures 10, 11 and 12. Flow (Q) values were obtained from head (H) readings by plotting Q versus H as determined from the weir formula to the point where H exceeded the extent of the V-notch of the weir. Once the tube was running full with varying H values, Q values were obtained according to the formula described in Appendix 3. The intermediate Q versus H values were obtained by interpolation to provide a continuous calibration curve. These calculated values approximated values obtained by

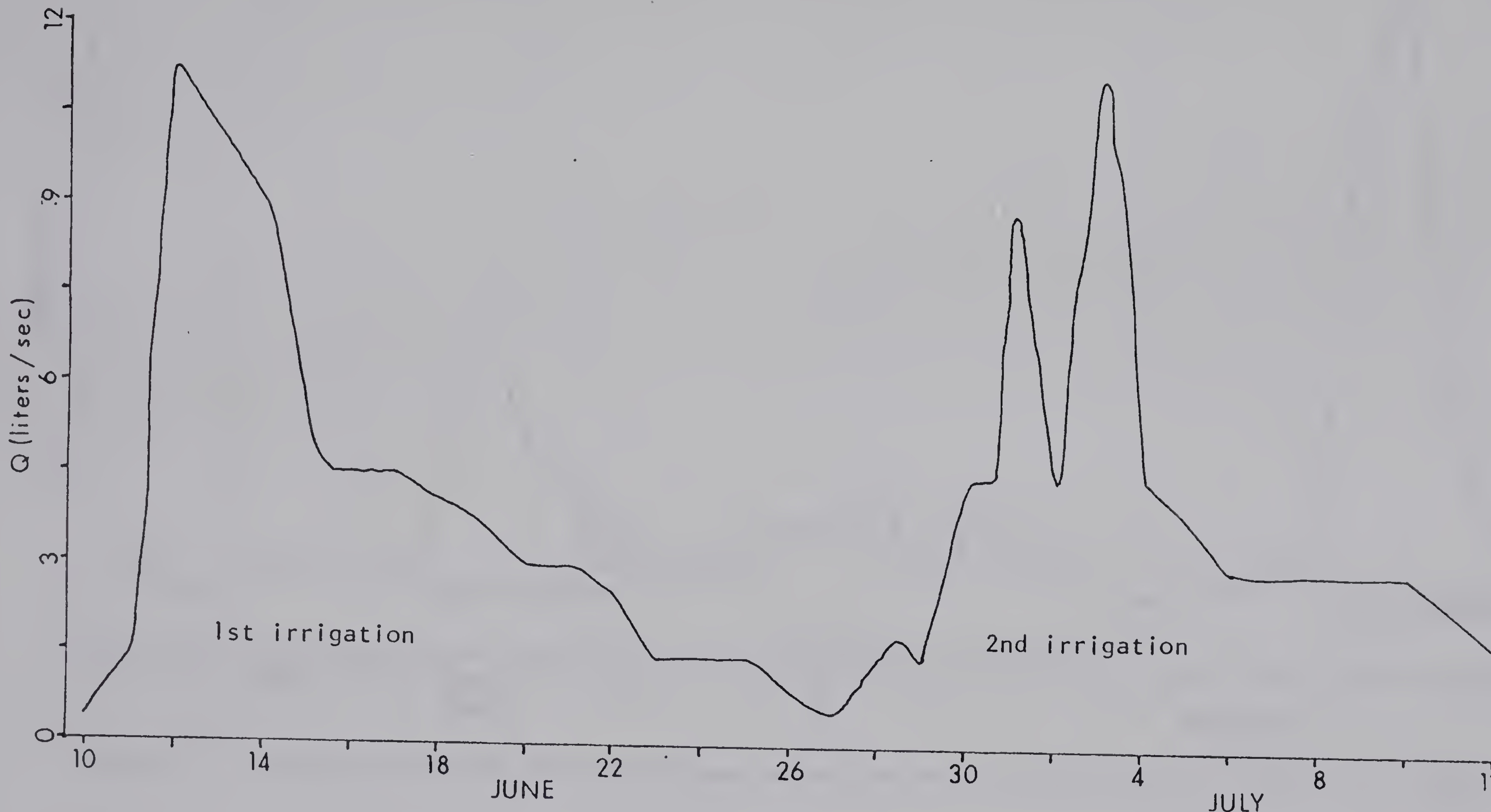


Figure 10. Discharge from the entire drainage system during first and second irrigations - 1977.

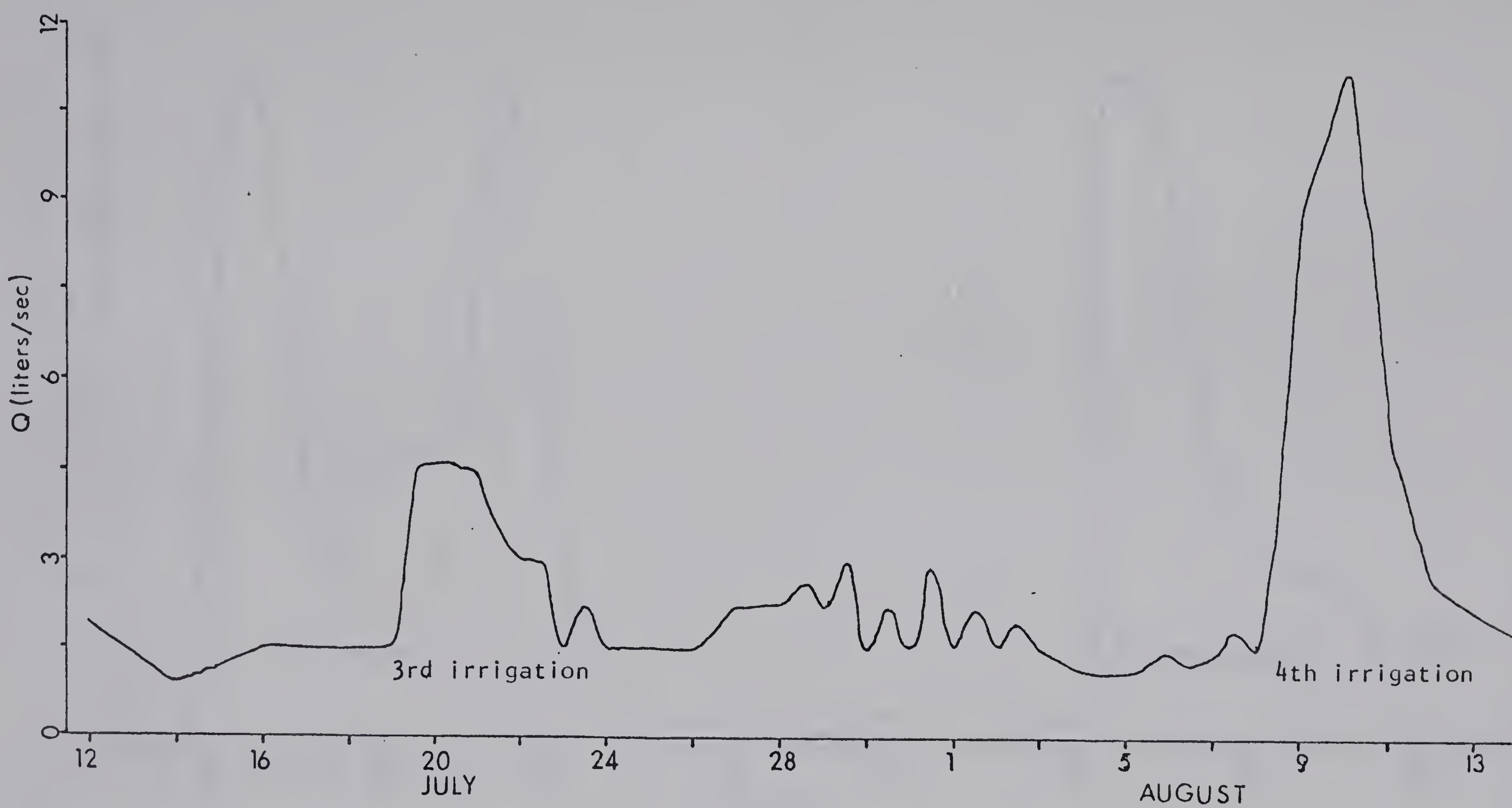


Figure 11. Discharge from the entire drainage system during third and fourth irrigations - 1977.

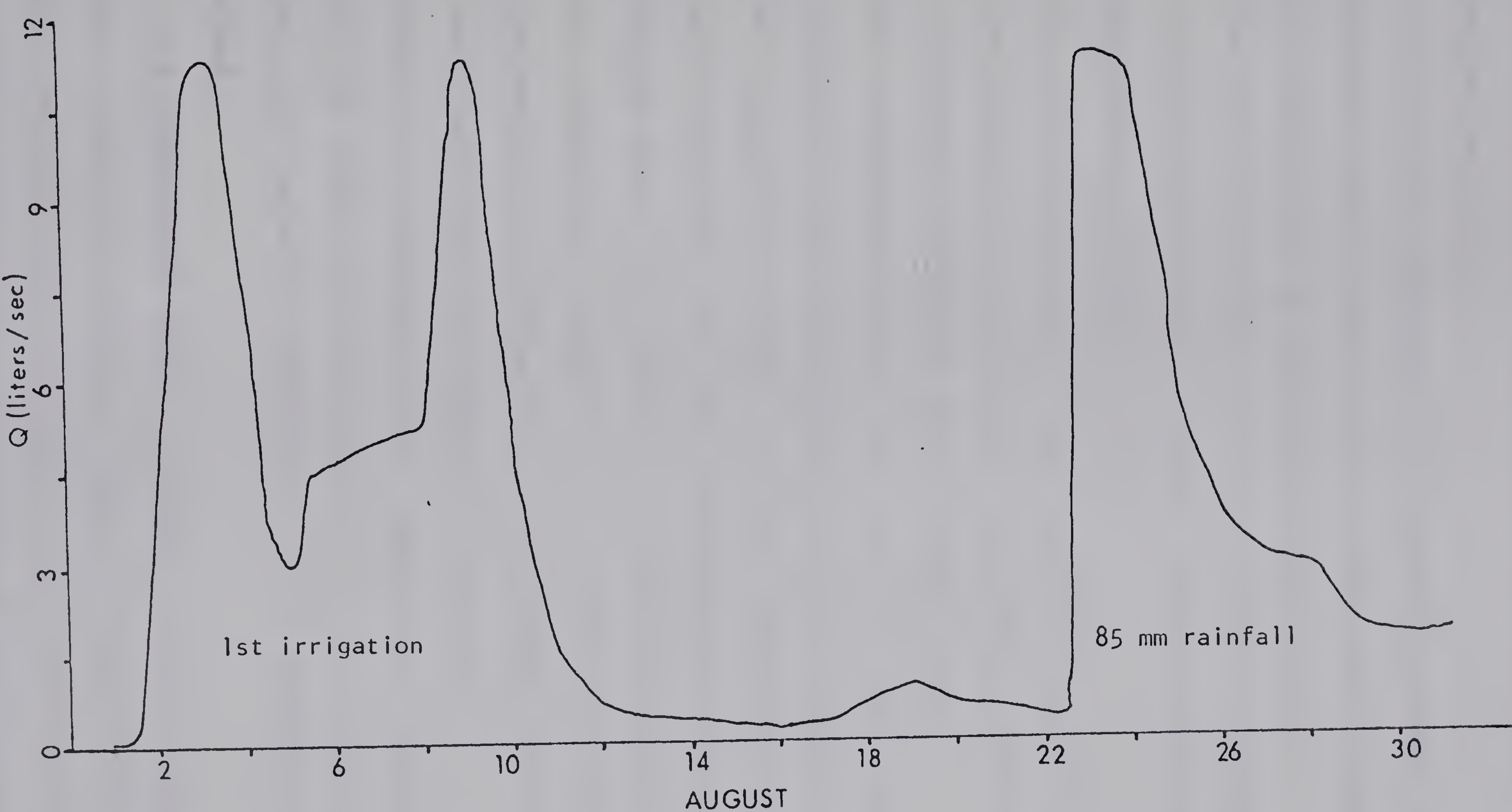


Figure 12. Discharge from the entire drainage system during first irrigation and a heavy (85 mm) rainfall - 1978.

manual calibration of flow with a stop watch and a calibrated container.

The extreme variability in the shape of the curves representing major fluctuations in flow can be explained in part by examination of surrounding conditions:

1. 1st irrigation (June 11 and 12, 1977): the farmer irrigated his volunteer barley and hay to the west following irrigation of site.
2. 2nd irrigation (July 2 and 3, 1977): the first peak corresponds to the farmer's irrigation, the second peak represents irrigation of the study area.
3. 3rd irrigation (July 19 and 20, 1977): the farmer irrigated after the irrigation of the research area.
4. 4th irrigation (August 8 and 9, 1977): the small initial peak represents the farmer's irrigation of his seeded barley after the volunteer barley was harvested.
5. 1st irrigation (August 1 to 3, 1978): the first peak corresponds to irrigation of the study area; the second peak represents the farmer's irrigation.

The farmer's irrigation of the remainder of the field, a portion of which was also underlain by the same drainage system, was the most influential factor affecting the curves obtained.

One observation which is common to all 6 major curves is the rather steep slope of the ascending portion of the curves. Another important point is that most of the curves have rather sharp peaks. The slopes of the descending

portion of the curves are also quite steep to a certain point, after which drainout continues sometimes for several days. Diurnal fluctuations in discharge were observed during the late growing season in 1977. These fluctuations could correspond to high evapotranspiration rates during that hot, dry period.

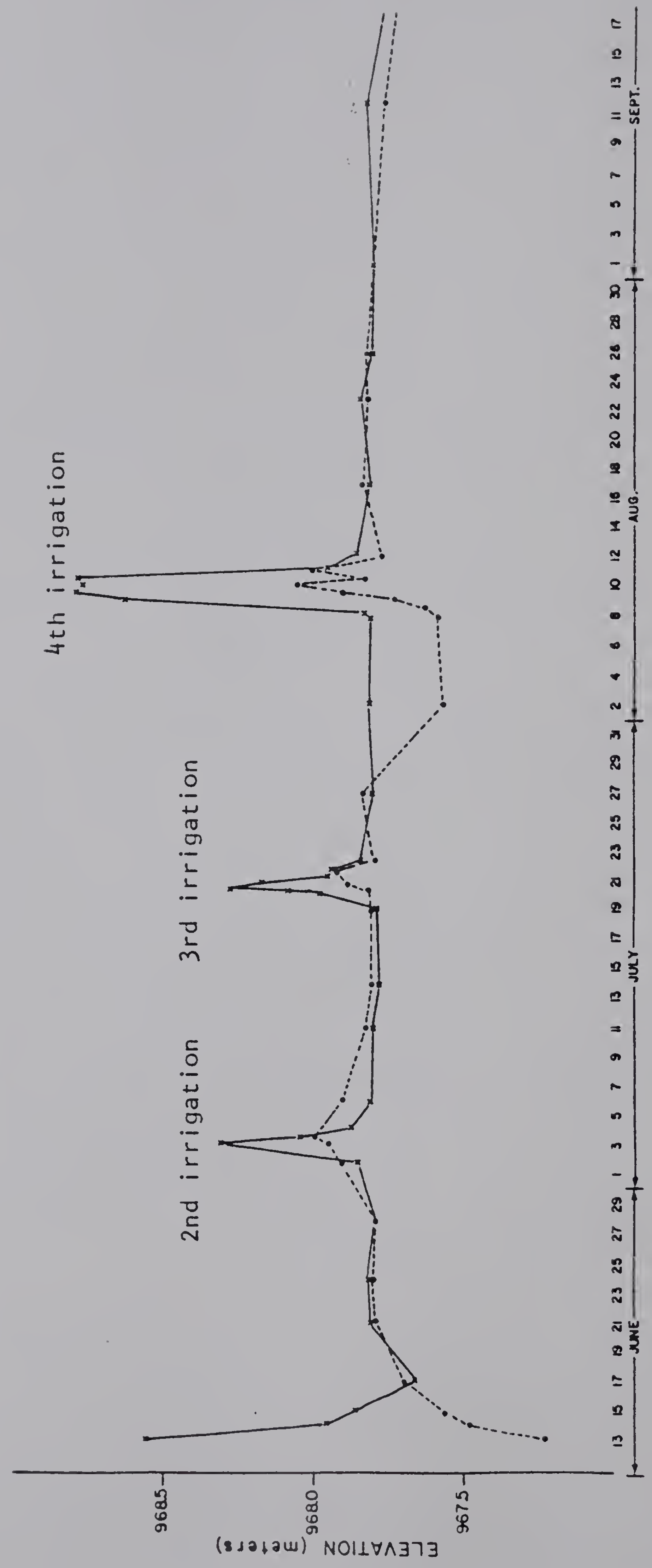
Comparison of these discharge hydrographs to the water table hydrographs previously examined for 1978 show that there is a very close relationship between the two. In other words, the drainage system does not appear to be backed up for very long periods of time and the system disposes of excess water very efficiently. The fact that the peaks are relatively sharp might indicate that the coarser layer behaves as a sink with high lateral K values wherein adjacent or early irrigation sets serve to fill the sink after which dramatic responses in water table levels and discharges are observed. This hypothesis is based on the assumption that applied water is moving rapidly through the soil profile, a point which will be examined later in the section on water movement through the soil profile.

Piezometer and Water Table Hydrographs

Piezometer hydrographs are presented for 1977 and 1978 in Figures 13 and 14. A large difference in hydraulic head was usually observed during irrigation periods between the 2 m (within coarse layer) and 4 m (below coarse layer) piezometers. Fluctuation of the head in the 4 m piezometer was usually minimal even during irrigation cycles. A downward hydraulic head was observed throughout most of the growing season during 1977 and 1978. Except for just prior to the fourth irrigation in 1977 (Figure 13), differences in hydraulic head between irrigations for the two depths of piezometers were not of great magnitude and can be explained by lag of the 2 piezometers in materials of different K values. The four peaks in the upper 1977 graph (Figure 13) represent 4 irrigations; the 2 peaks in 1978 (Figure 14) represent one irrigation and a heavy rainfall.

Substantial hydraulic head differences during irrigation cycles cannot be interpreted as meaning there is significant water movement from the coarser layer downward through the SiC material. The differences in hydraulic head simply indicate the existence of a potential discharge or recharge situation which exists.

Figure 15 portrays water table and piezometer hydrographs for the fourth irrigation in 1977 (August 8 and 9). A comparison of the shallow piezometer to the 3 water table wells on the same border dyke indicates that they all behave in a similar manner. The maximum water level was


4th irrigation
3rd irrigation
2nd irrigation
ELEVATION (meters)
968.5
968.0
967.5
13 15 17 19 21 23 25 27 29
JUNE
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31
JULY
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
AUG.
1 3 5 7 9 11 13 15 17
SEPT.

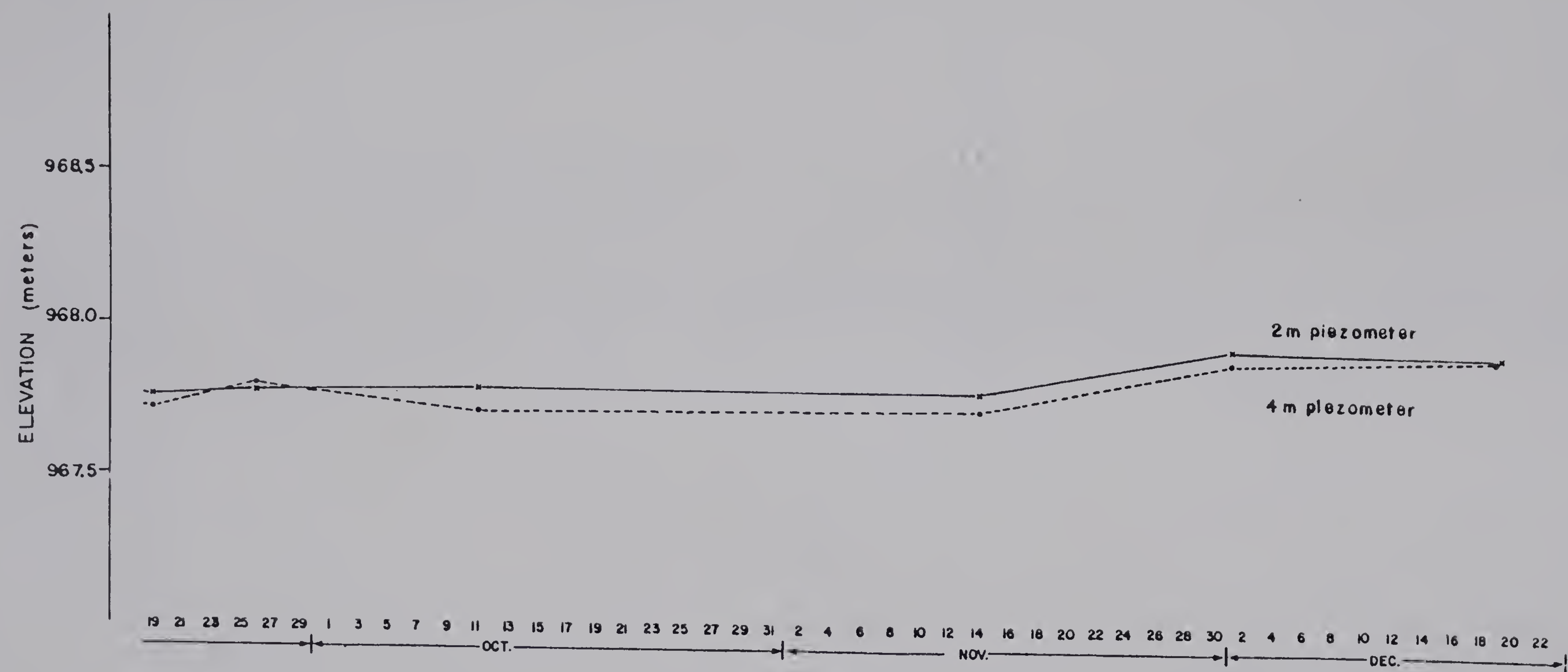
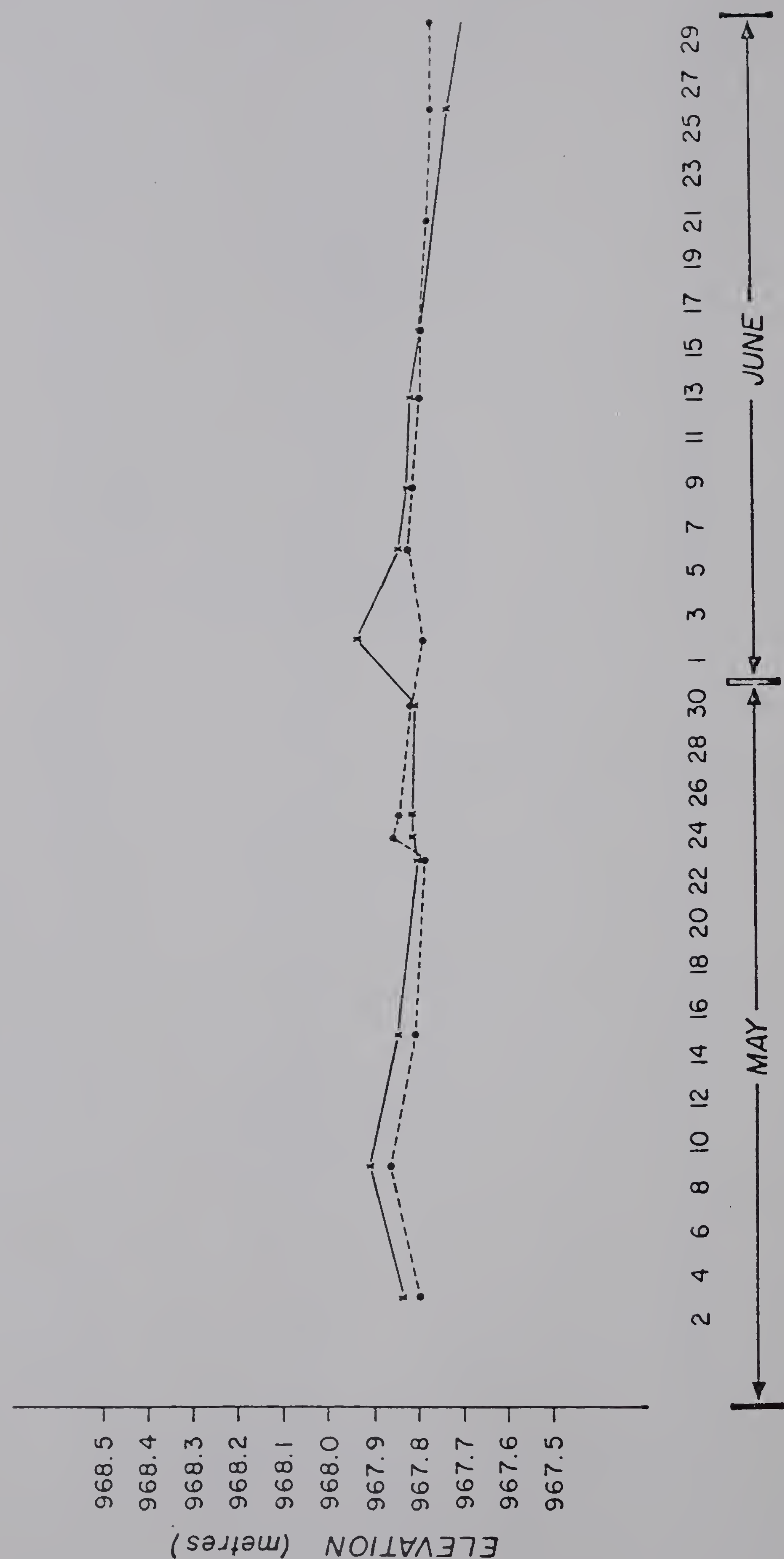


Figure 13. Piezometer hydrographs - 1977.


ELEVATION (metres)
968.5
968.4
968.3
968.2
968.1
968.0
967.9
967.8
967.7
967.6
967.5
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29
MAY
JUNE

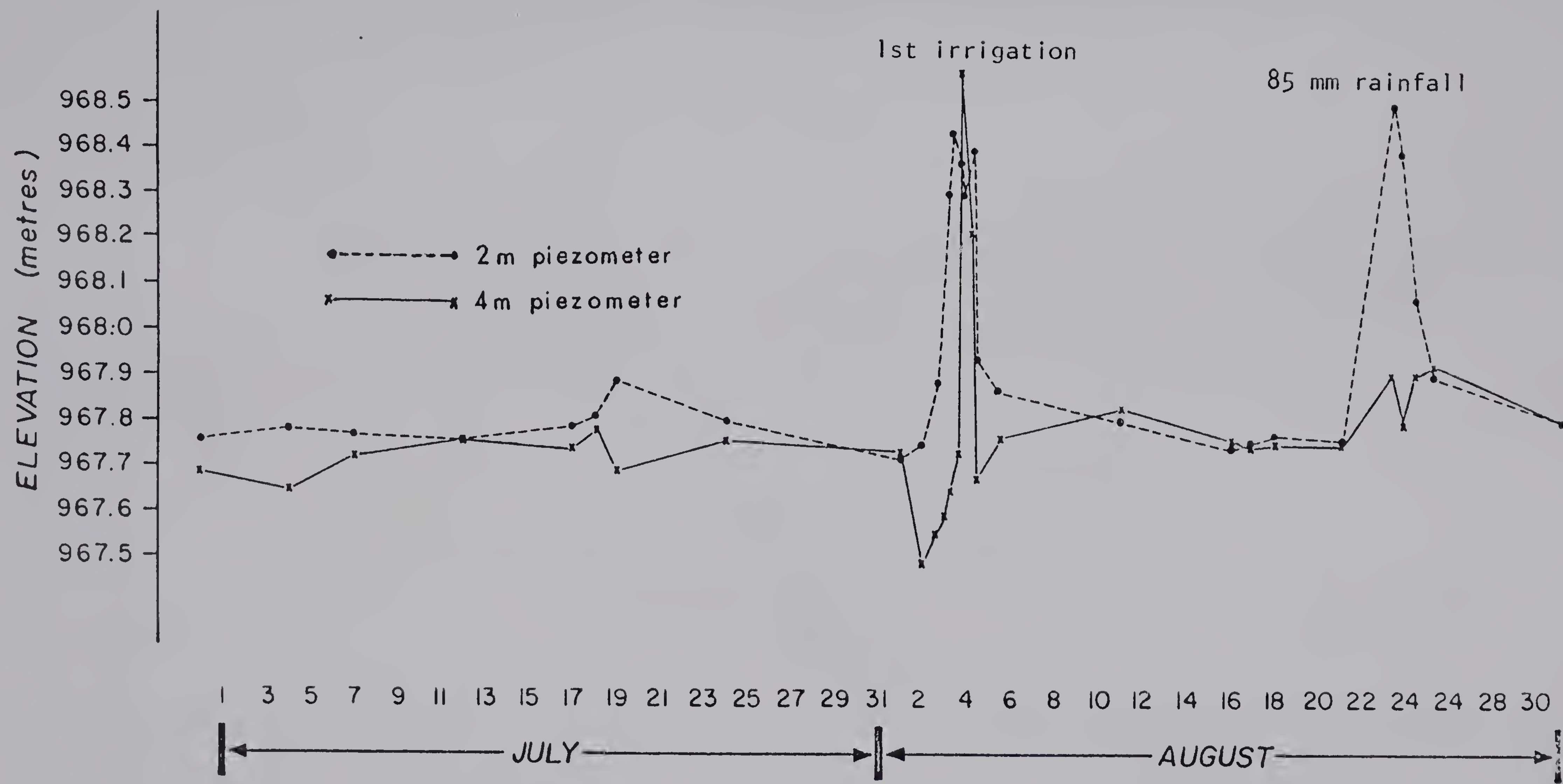
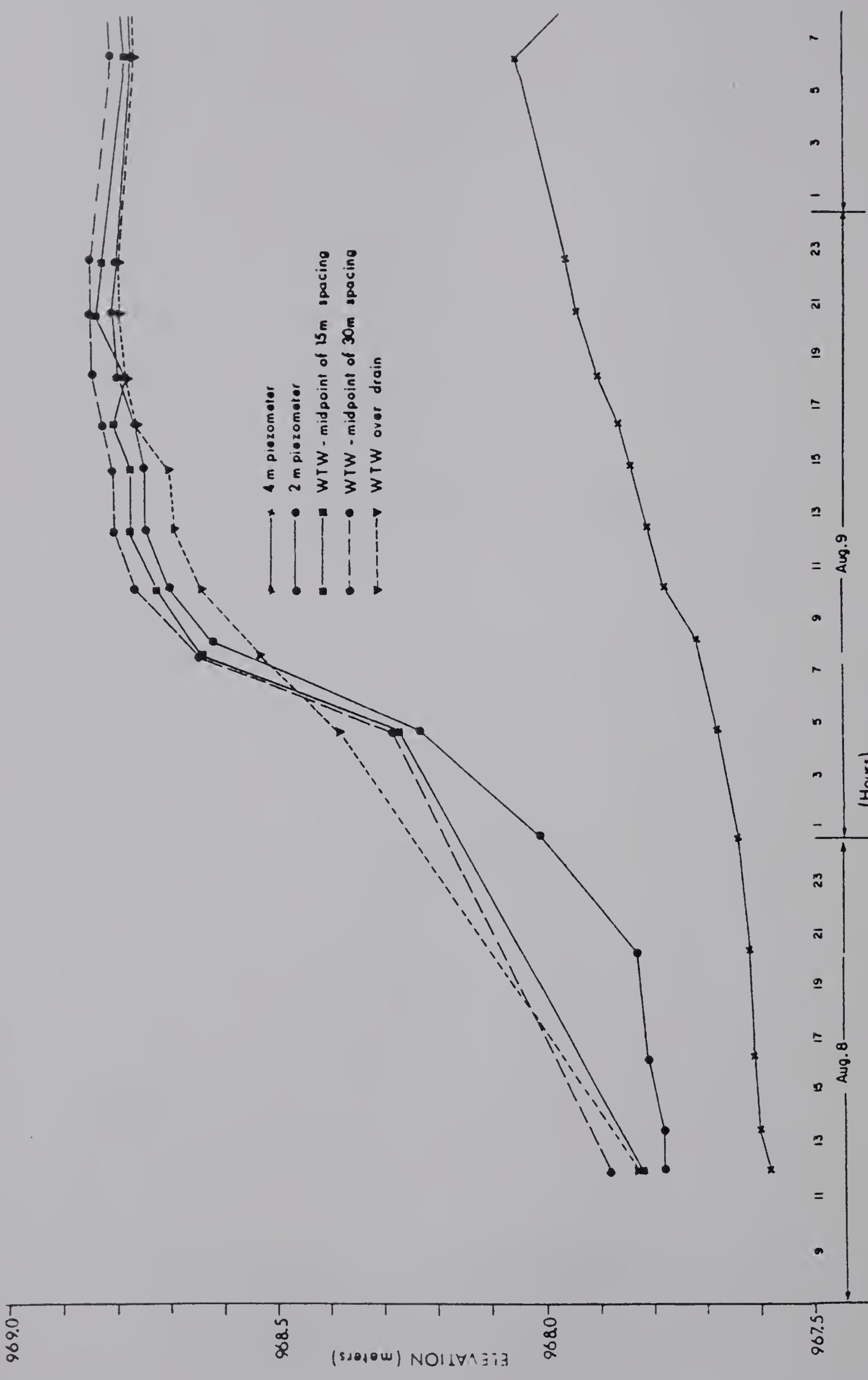


Figure 14. Piezometer hydrographs - 1978 growing season.


4 m piezometer
2 m piezometer
WTW - midpoint of 15m spacing
WTW - midpoint of 30m spacing
WTW over drain
ELEVATION (meters)
969.0
968.5
968.0
967.5
9
11
13
15
17
19
21
23
1
3
5
7
9
11
13
15
17
19
21
23
1
3
5
7
Aug. 8
Aug. 9
(Hours)

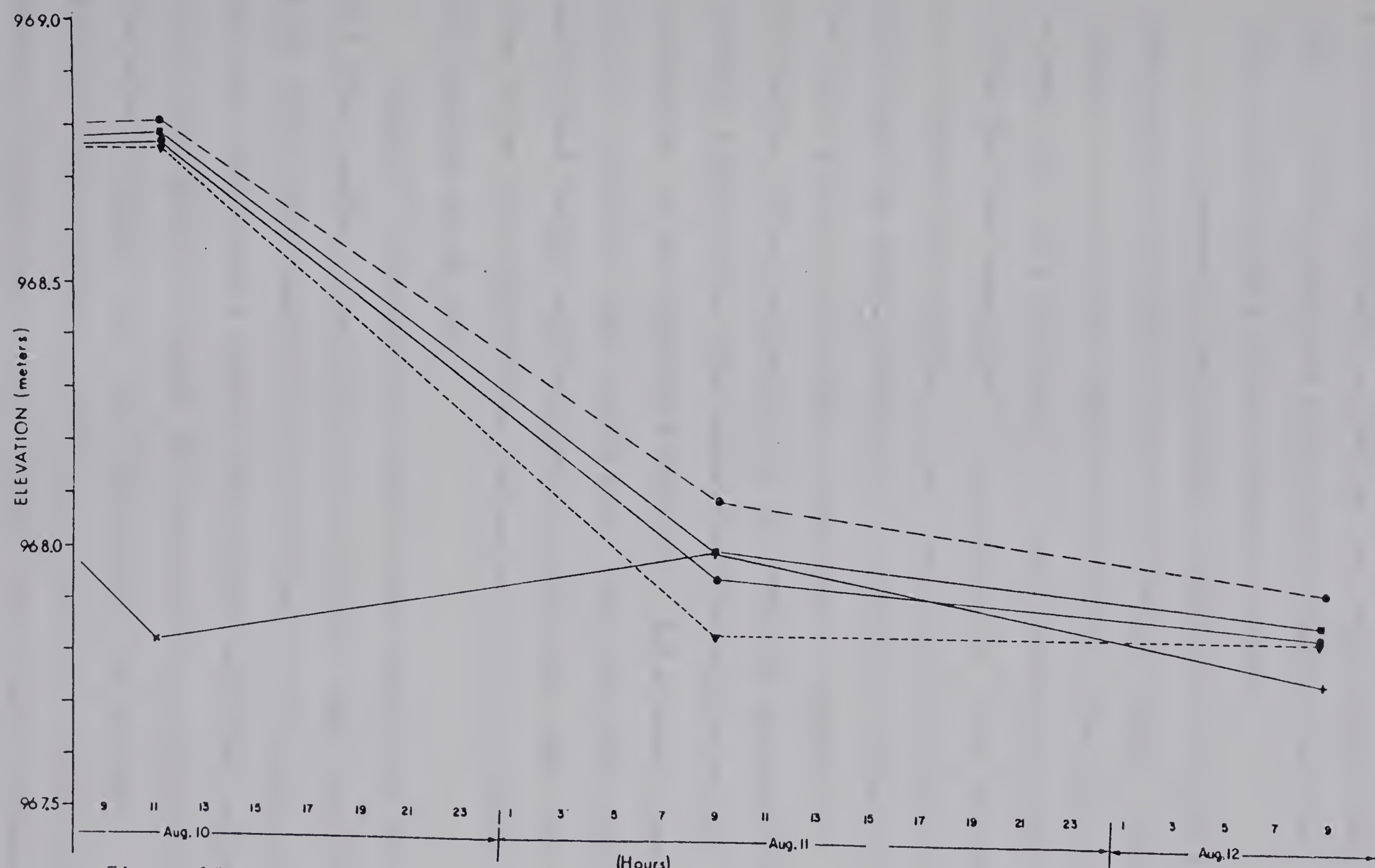
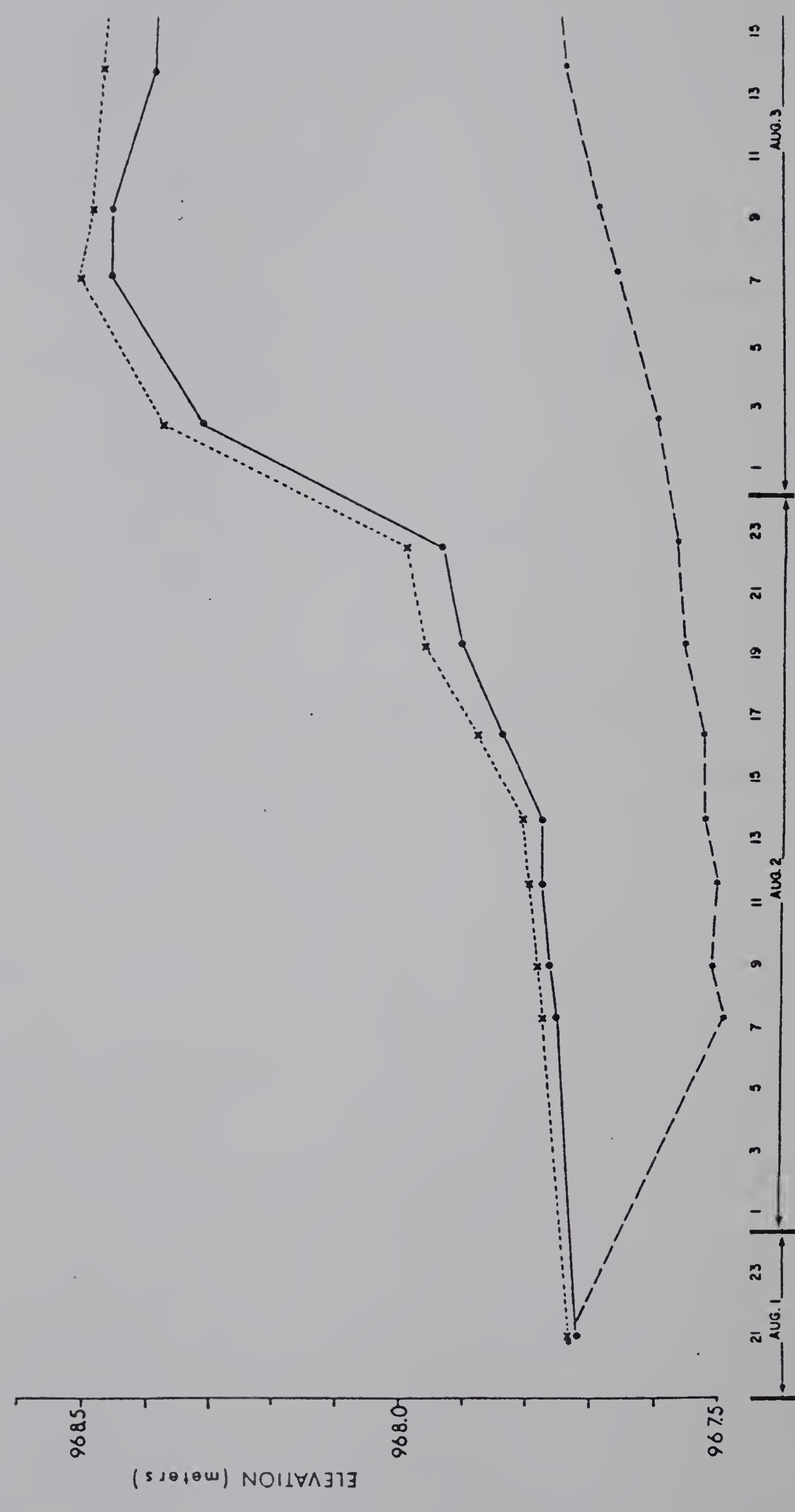


Figure 15. Piezometer and water table hydrographs for fourth irrigation - 1977.

similar in all four (within 30 cm of surface) whereas the 4 m piezometer did not respond to the same degree. The water level receded within 48 hours. This fluctuation also corresponds closely to the discharge curves.

The piezometer hydrographs illustrated in Figure 16 correspond to the first and only 1978 irrigation cycle (August 1 to 3). Both shallow piezometers have very similar curves. The 1.5 m piezometer is also situated in the same border but was installed in the spring of 1978. The maximum water levels are somewhat lower than those in Figure 15. The fact that the farmer irrigated his adjacent fields prior to the test site in 1977 (4th irrigation) as opposed to irrigation after the test site in 1978 may account for the greater fluctuation. The anomalous fluctuation of the 4 m piezometer is not explained but the 2 data points suggest that the readings were legitimate. High hydraulic heads were maintained during the irrigation period and about the same time frame was required for recession of water levels in the piezometers as in 1977.

Figure 17 represents a water table hydrograph for the D-8 West border. Fluctuation of the water table over the tile lines was compared to the midpoints of the two spacings for the 1977 growing season. The graphs show that water levels are slightly higher at the midpoints of both spacings compared to right over the lines during and between irrigations. Variability in the maximum water levels for the various irrigations is also shown. These peaks correspond


ELEVATION (meters)
968.5
968.0
967.5
AUG. 1
AUG. 2
AUG. 3
21 23 1 3 5 7 9 11 13 15 17 19 21 23 1 3 5 7 9 11 13 15

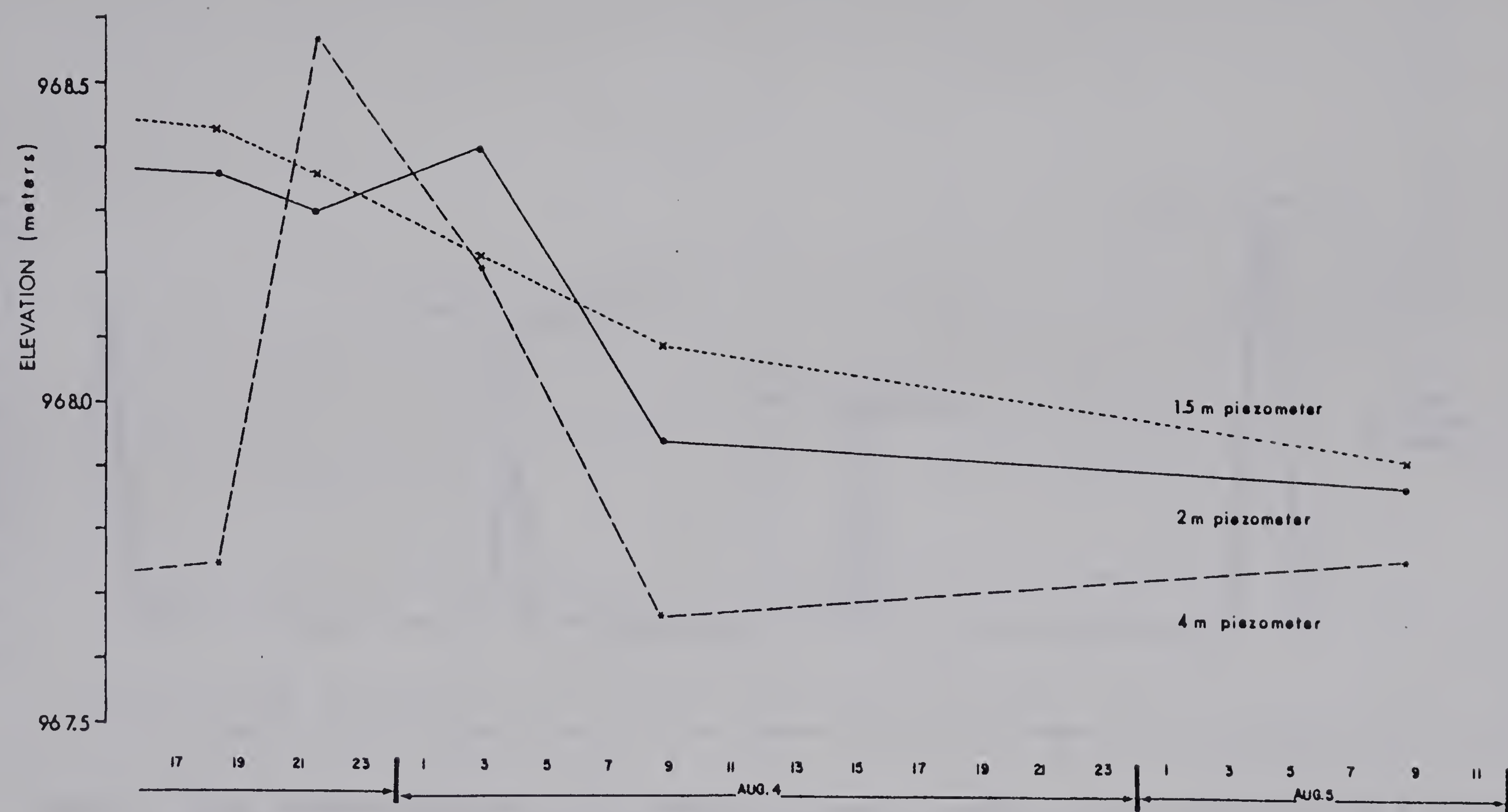


Figure 16. Piezometer hydrographs for first irrigation - 1978.

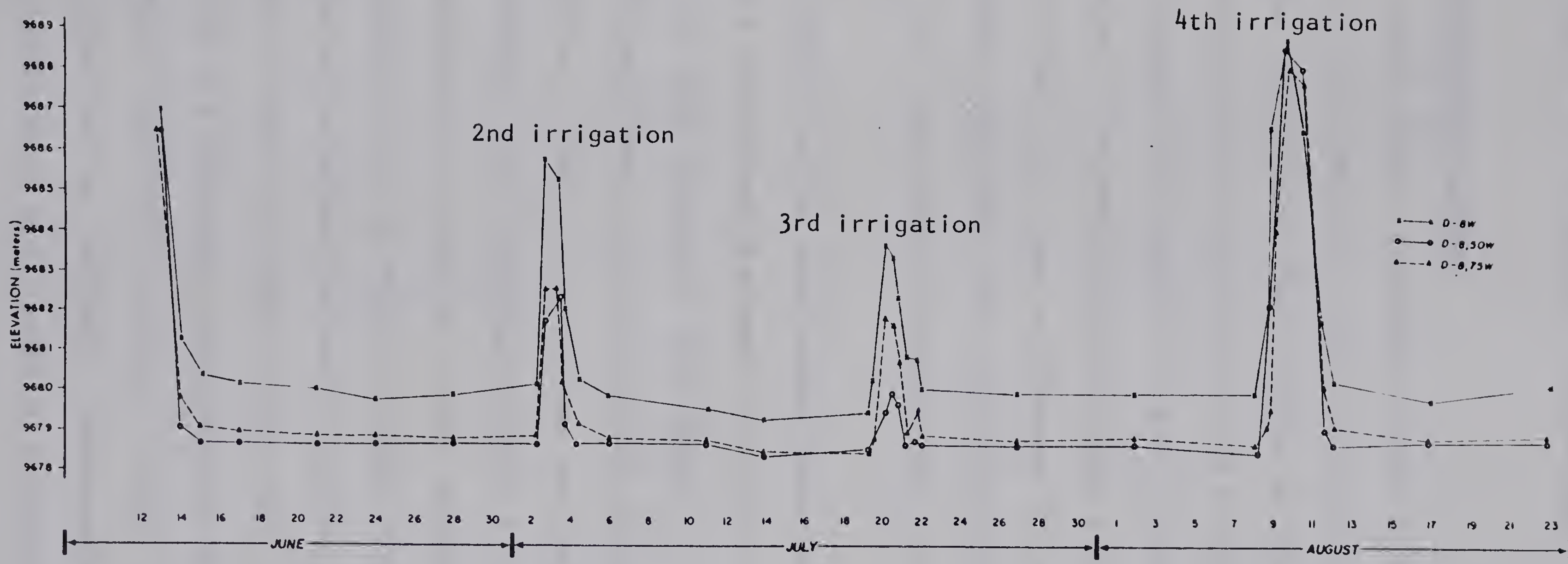


Figure 17. Water table hydrographs (1977) showing response of water table at midpoint of 30 m spacing (W); midpoint of 15 m spacing (75W); and over tile line (50W).

closely to those for discharge of individual tile lines.

Water Table Recession Curves

Several water table recession curves are depicted in Figures 18 to 21 for various series of water table wells across the site (Figure 2). The circles on the graphs represent the approximate location of the tile lines. These locations are suspect in Figures 18 and 20 where the actual location appears to be above the designed elevations whereas the location of the tile line in Figures 19 and 21 appears reasonable. These locations were estimated from probing attempts for the lines and extrapolation from the designed slope.

Several points can be made about these drawdown curves. There is little difference between the shape of the curves for the 15 m and 30 m spacings. The shapes of the curves for the various borders show a great deal of variability between locations, however, most of the curves are relatively flat with major drawdown only occurring directly above the tile lines. Some variability occurred in the recession times for the various applications of water although recession times between borders are similar for each application. The maximum height to which the water table rose varied considerably for the different applications but remained comparable for the different series of water table wells during each irrigation or rainfall. Surrounding conditions, as discussed previously, were partially responsible for this

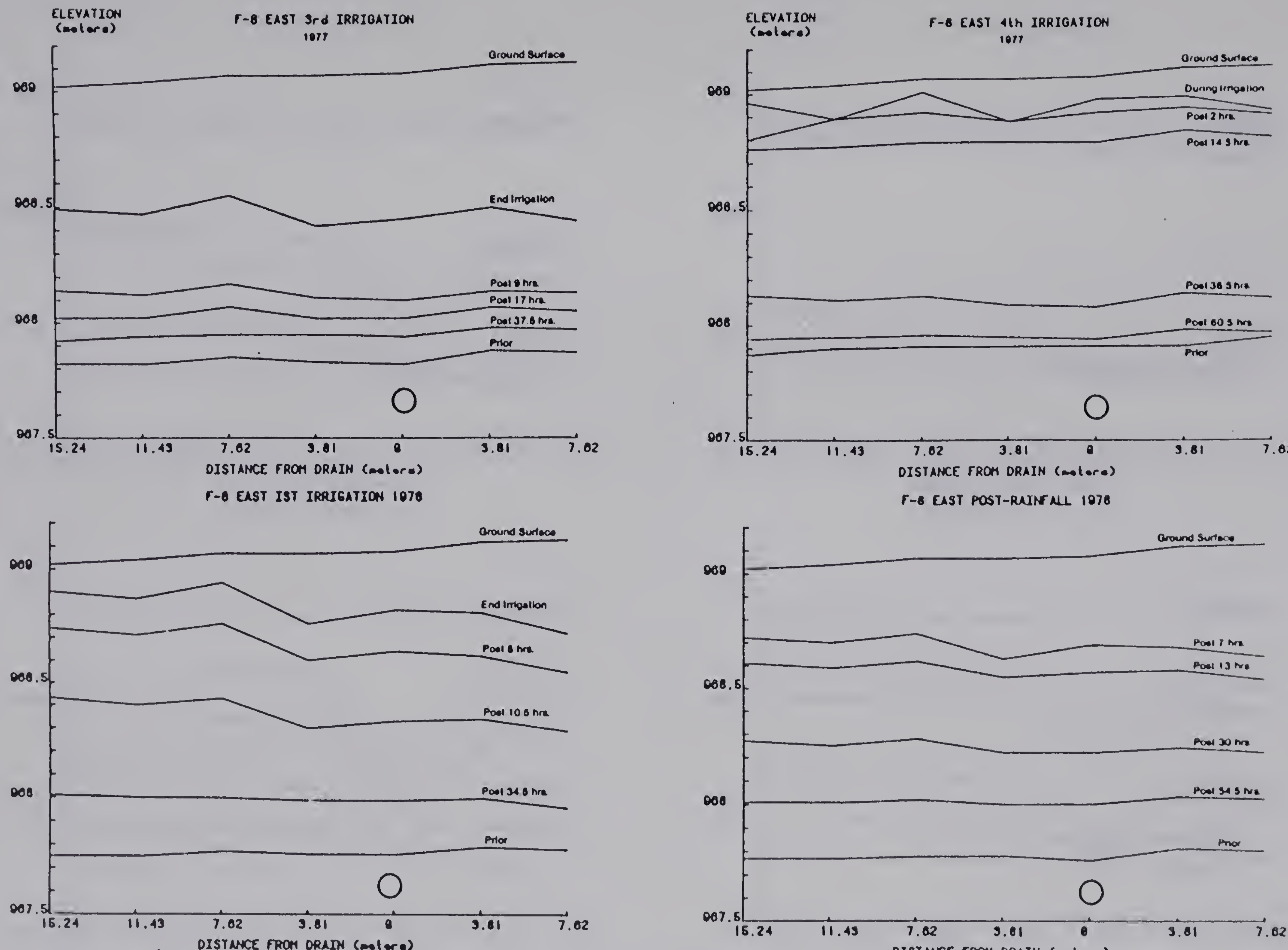


Figure 18. Water table recession curves on F-8 East.

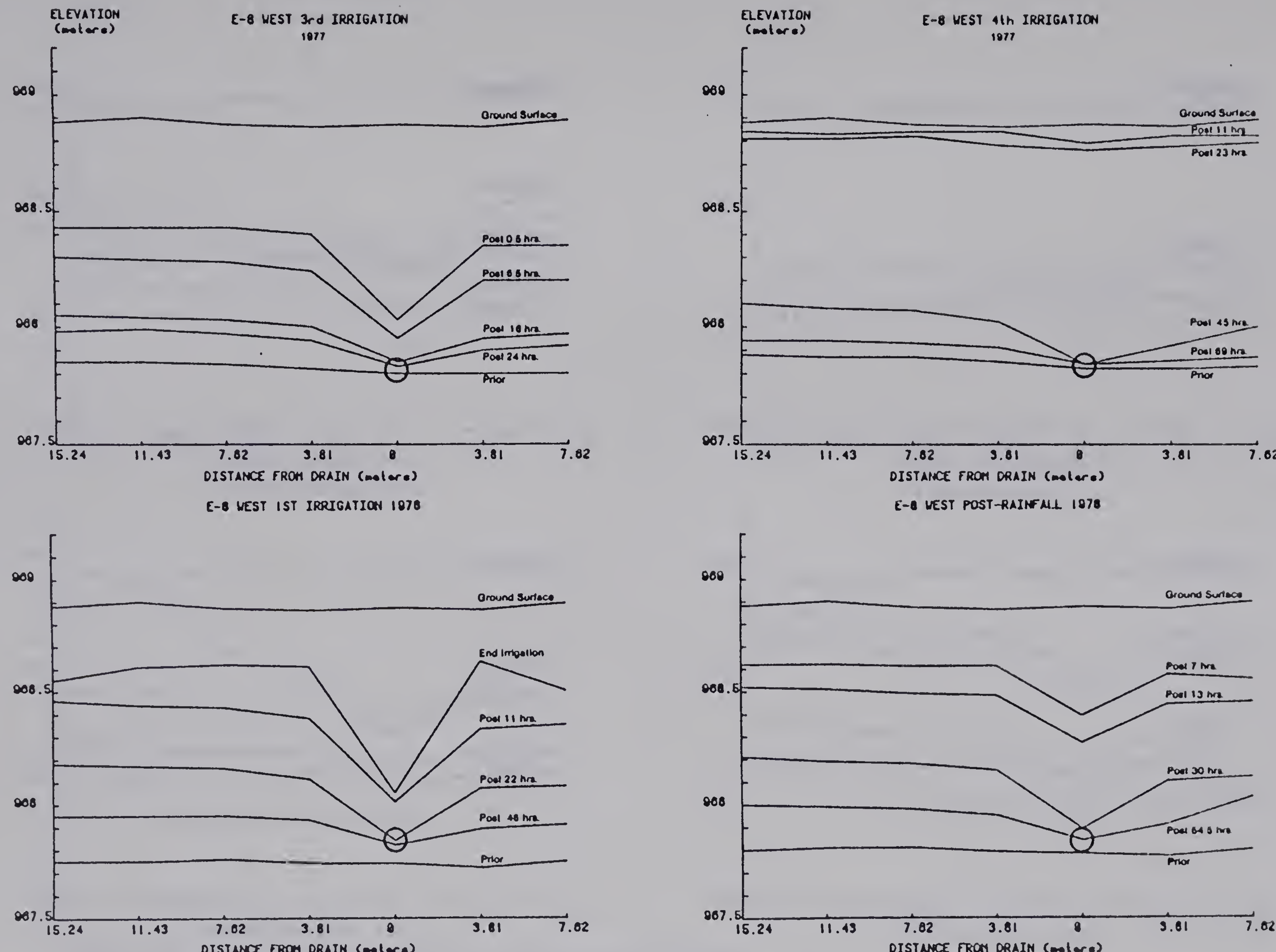


Figure 19. Water table recession curves on E-8 West.

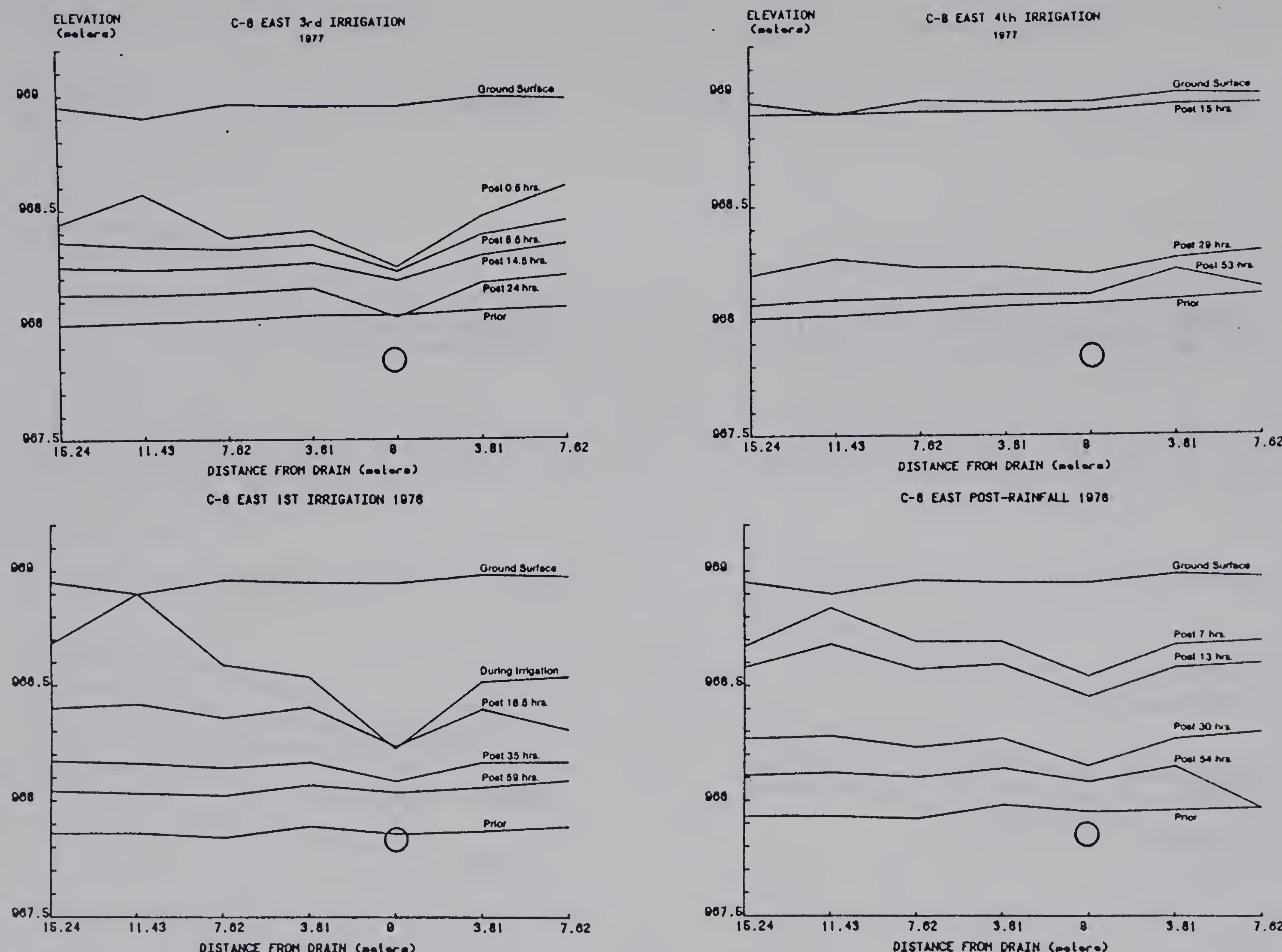


Figure 20. Water table recession curves on C-8 East.

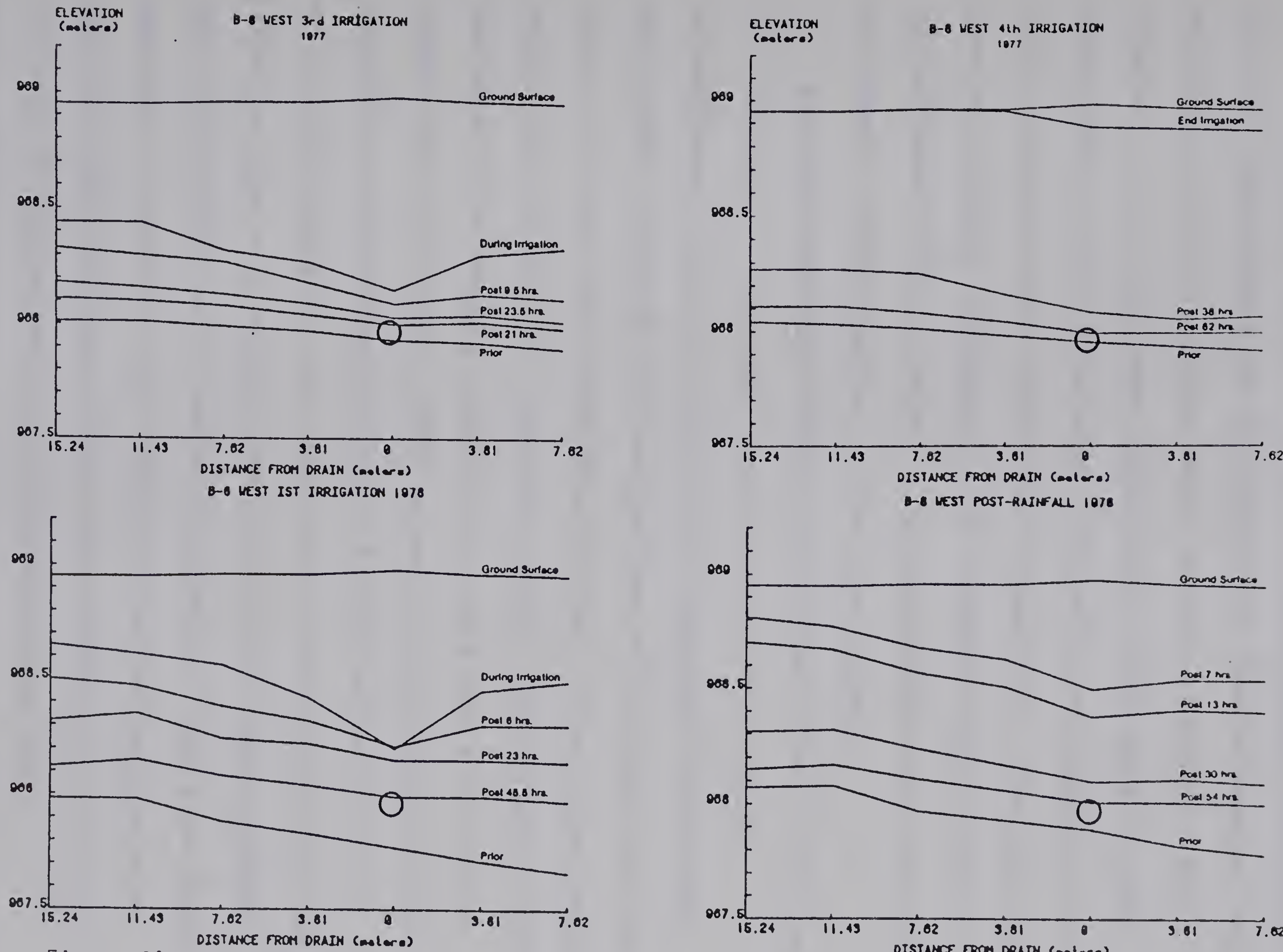


Figure 21. Water table recession curves on B-8 West.

response.

The water table receded extremely rapidly throughout the site with return to pre-irrigation levels nearly always occurring within 48 hours. Van't Woudt and Hagan (1957) suggest that a high water table does little harm to most crops until 3 or 4 days after irrigation or rainfall. Tovey (1964) reported that removal of excess water from the root zone of alfalfa, adapted to a 60 cm water table, must be accomplished within 3 days to retain optimum crop production and prevent deterioration of the root system.

Previous drainage studies in southern Alberta indicated that drainage of the soil profile to 60 cm could be accomplished within or close to the specified time frame. Rapp (1968) reported drainout periods of 4.0 days for tile drains, 5.9 days for lined mole drains, 6.0 days for unlined moles, and 6.4 days for the check plots. These values imply potential root damage, particularly with the mole drains. Sommerfeldt and Paziuk (1975) showed that the water table receded to a 90 cm depth within 29 hours after 96 cm of water infiltrated into the soil profile and caused the water table to rise to a depth of 60 cm. Both of these studies took place within areas containing Shallow Chin loam soils developed on glacial till. Results from the Magrath site indicate that recession of the water table was very rapid, in spite of the apparent low permeability of the fine-textured upper soil material.

Water Balances

Another means of assessing the performance of the drainage system, in addition to water table recession, is calculation of a water balance and drainage yield for each application of water (Table 12). The quantity of water added was equated to evapotranspiration, runoff, discharge and storage in the soil profile. The amount of water applied was estimated from the discharge rate of the syphon tubes used for irrigation and from the rain gauge for the rainfall. A discharge formula (Israelsen and Hansen, 1962) for the 90 degree V-notch weir used to estimate runoff, provided estimates as to the amount of runoff that occurred for the first irrigation in 1978. Runoff estimates for 1977 irrigations were taken as one quarter the amount of water applied, since runoff was allowed to continue from each border for about one quarter the time it took water to reach the end of the runs. Evaporation from the site was estimated from data compiled by personnel from Alberta Agriculture at four locations within a 40 km radius of the site. These values are averages of the four locations. Discharge was determined from the constant recorder hydrographs (Figures 10, 11, and 12). The amount of water stored in the soil was estimated by the difference between the amount of water applied and the various losses due to runoff, evapotranspiration and discharge through the drainage system. Losses of water due to deep percolation and lateral movement outside the drained area are therefore included in

Table 12. Water balances for 3 irrigations in 1977 and 1 irrigation and an 85 mm rainfall in 1978.

	Water Applied	Runoff	Evapotranspiration (liters X 10^6)	Discharge	Storage	Storage (cm)
1977						
Second irrigation	7.27	1.82	1.21	2.03	2.21	3.8
Third irrigation	13.26	3.31	1.32	2.82	5.81	9.7
Fourth irrigation	11.78	2.94	0.55	2.89	5.39	9.1
1978						
First irrigation	12.81	0.07	0.81	2.34	9.59	16.0
Rainfall (85 mm)	6,89	nil	0.47	3.24	3.17	5.3

this storage component.

There are a number of factors which contribute to the wide variation in water balances for the separate irrigations. Runoff was controlled for the most part by the method of irrigation, evaporation fluctuated with climatic conditions as did the amount of moisture stored in the soil. The application of water to areas immediately adjacent to the study area had a significant influence on these water balance estimates. This influence was difficult to predict since the effect of the surrounding conditions was not measured. The discharge estimates are somewhat conservative in that the drainout period continued for as long as 2 weeks after irrigations, although the recession limbs after 4 days were disregarded since discharge was almost at pre-irrigation levels and reliable estimates as to the influence of other factors became more difficult. Fluctuations in head at the supply ditch also contributed to variability in water application rates over the different borders even though care was taken to ensure that a 15 cm head was maintained throughout each irrigation. Difficulties encountered during the 1978 irrigation necessitated lengthening the irrigation sets to compensate for irreversible reductions in head.

The several sources of error in these water balances illustrate the difficulty experienced in accurately measuring all the factors involved in such an estimation. In Table 12 the values for the three 1977 irrigations and the

rainfall in 1978 appear to be the most realistic, whereas the 1978 irrigation is particularly suspect with respect to the amount of water stored in the soil profile. About 12 cm of water are all that could possibly be stored in the soil profile.

Drainage yields were calculated for each application of water. This term is defined (Rapp, 1962) as the volume of drainage outflow expressed as a percentage of the total volume of water applied. Drainage yields were found to be 28, 21, 24, 18 and 47%, respectively, for the 5 water applications. The value for the rainfall (47%) may be due to drainage from outside the area.

C. Evaluation of Salinity Control

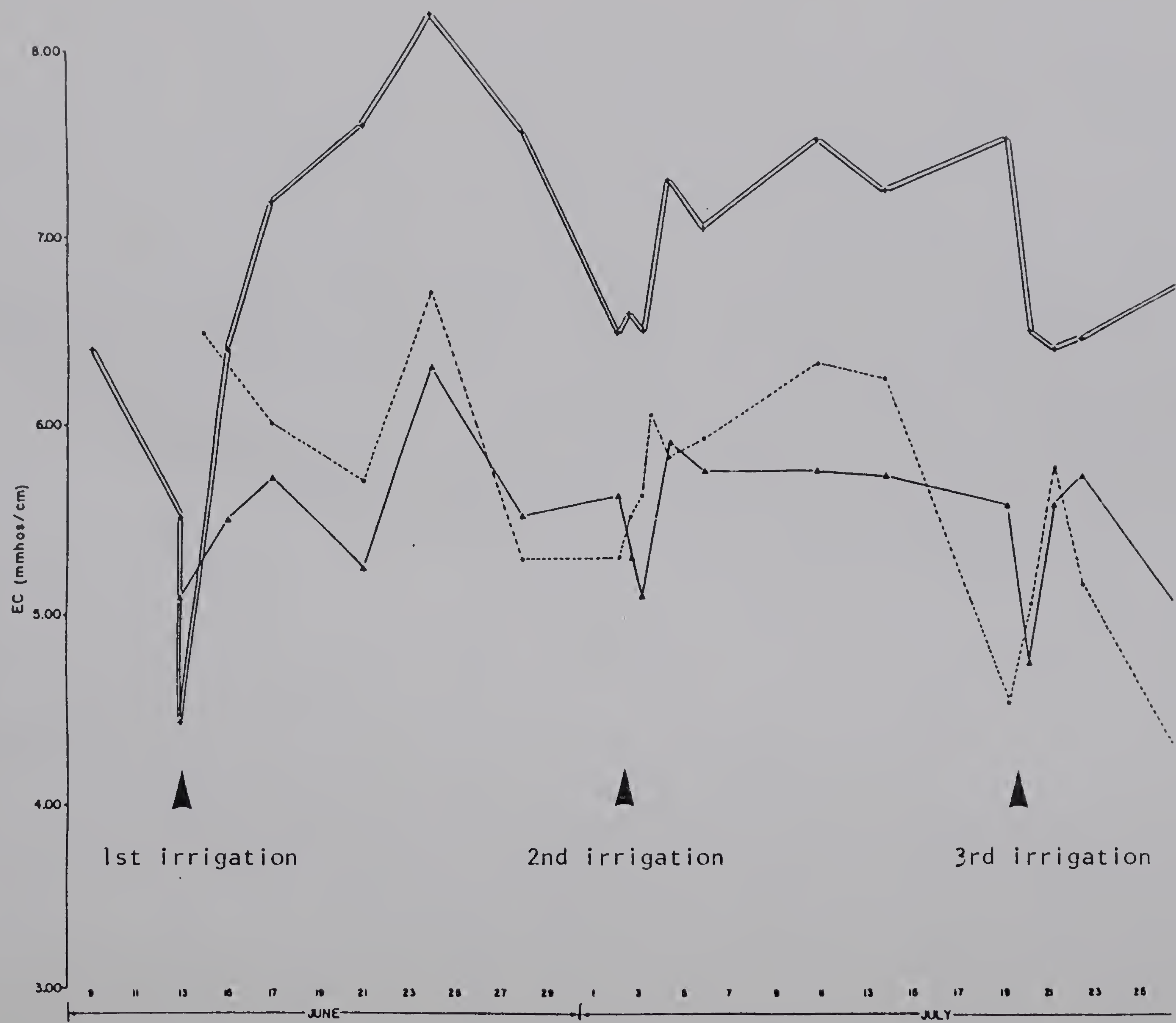
Water quality of the drainage effluent over time and the distribution of salts in the soil profile with respect to depth and to distance from the tile lines were the main tools used in this study for appraising the salinity-reclamation process.

Water Quality of Effluent

Water quality of the drainage effluent during the course of this study is presented in Figures 22 to 25. These graphs show EC and SAR values of effluent samples derived from two tile lines and from the drainage system as a whole.

Throughout 1977 the range in water quality remained constant from June to mid-September. Maximum fluctuations occurred during irrigation periods showing a dilution effect of 1 or 2 EC or SAR units. Christie (1968) found that drainage effluent from an interceptor drain some 150 m to the west had exhibited similar results in that there was essentially no change in the constituents of the drainage water over a year of study. These observations suggest that continuous discharge of saline groundwater was responsible for maintaining the salt composition and concentration at a relatively constant level throughout the period of investigation.

During 1978 (Figures 24 and 25) the effluent water quality was comparable to the range observed in 1977 but more erratic trends for samples from different sources were also noted. No major improvement in water quality was observed, as might be expected if rapid reclamation of the site was taking place; however, vast quantities of salts were removed by the drainage system (Appendix 4). These numbers reflect the intrusion of salts from outside the study area as well as the reserve of salts within the soil profile.



8.00
7.00
6.00
5.00
4.00
3.00
EC (mmhos/cm)
1st irrigation
2nd irrigation
3rd irrigation
JUNE
JULY

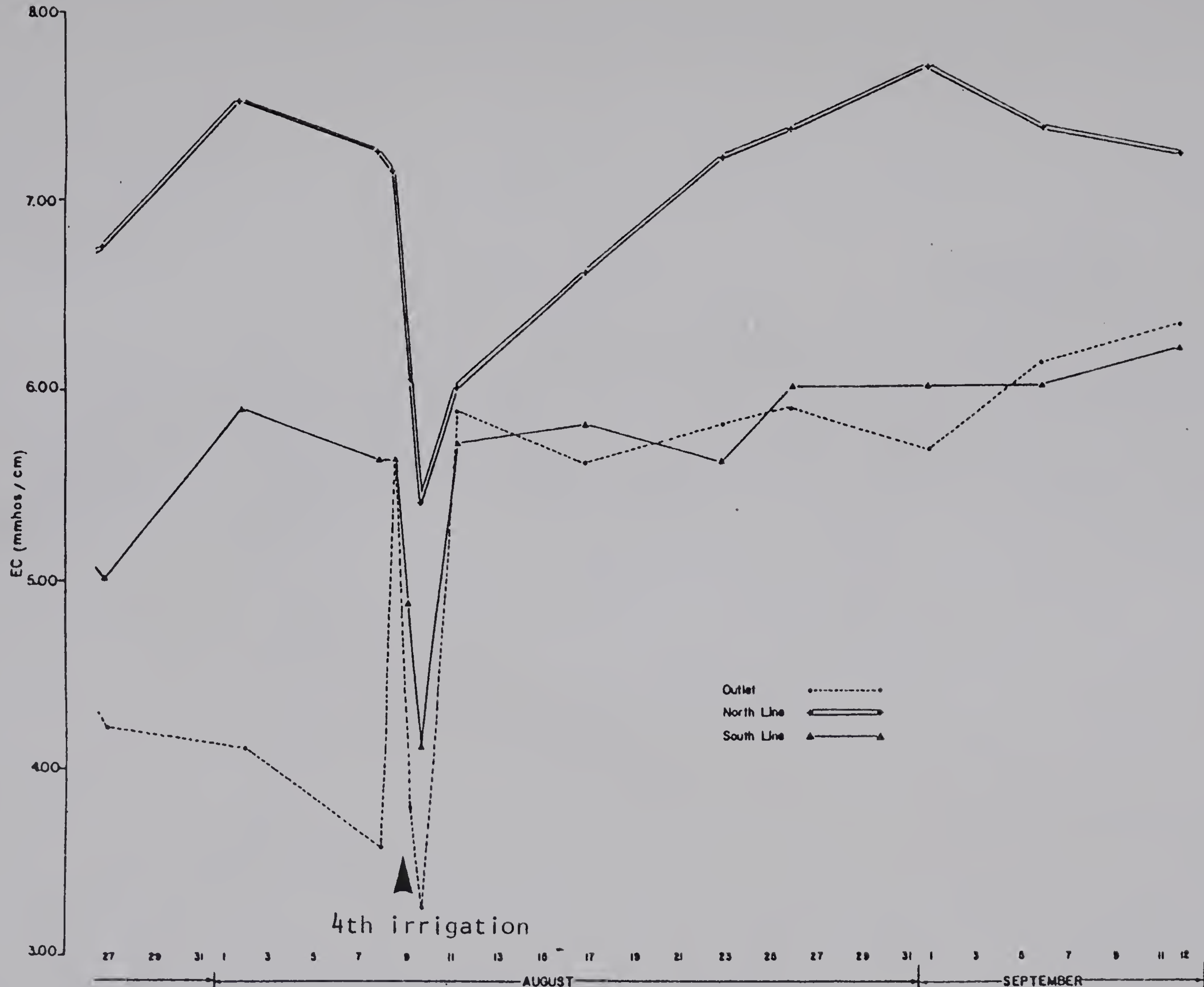
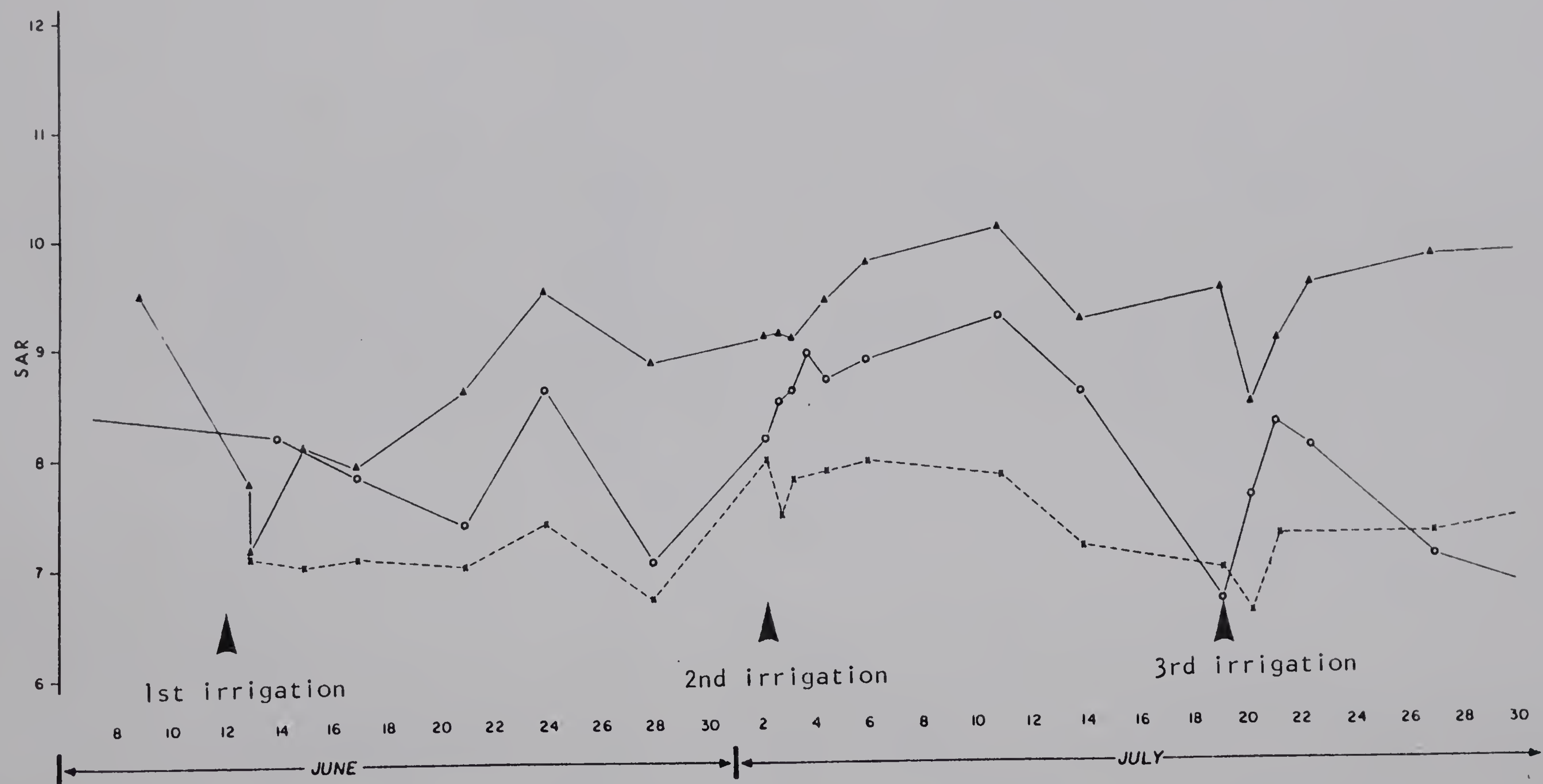


Figure 22. Electrical conductivity of drainage effluent over 1977 growing season.



12
11
10
9
8
7
6
SAR
1st irrigation
2nd irrigation
3rd irrigation
8 10 12 14 16 18 20 22 24 26 28 30 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
JUNE
JULY

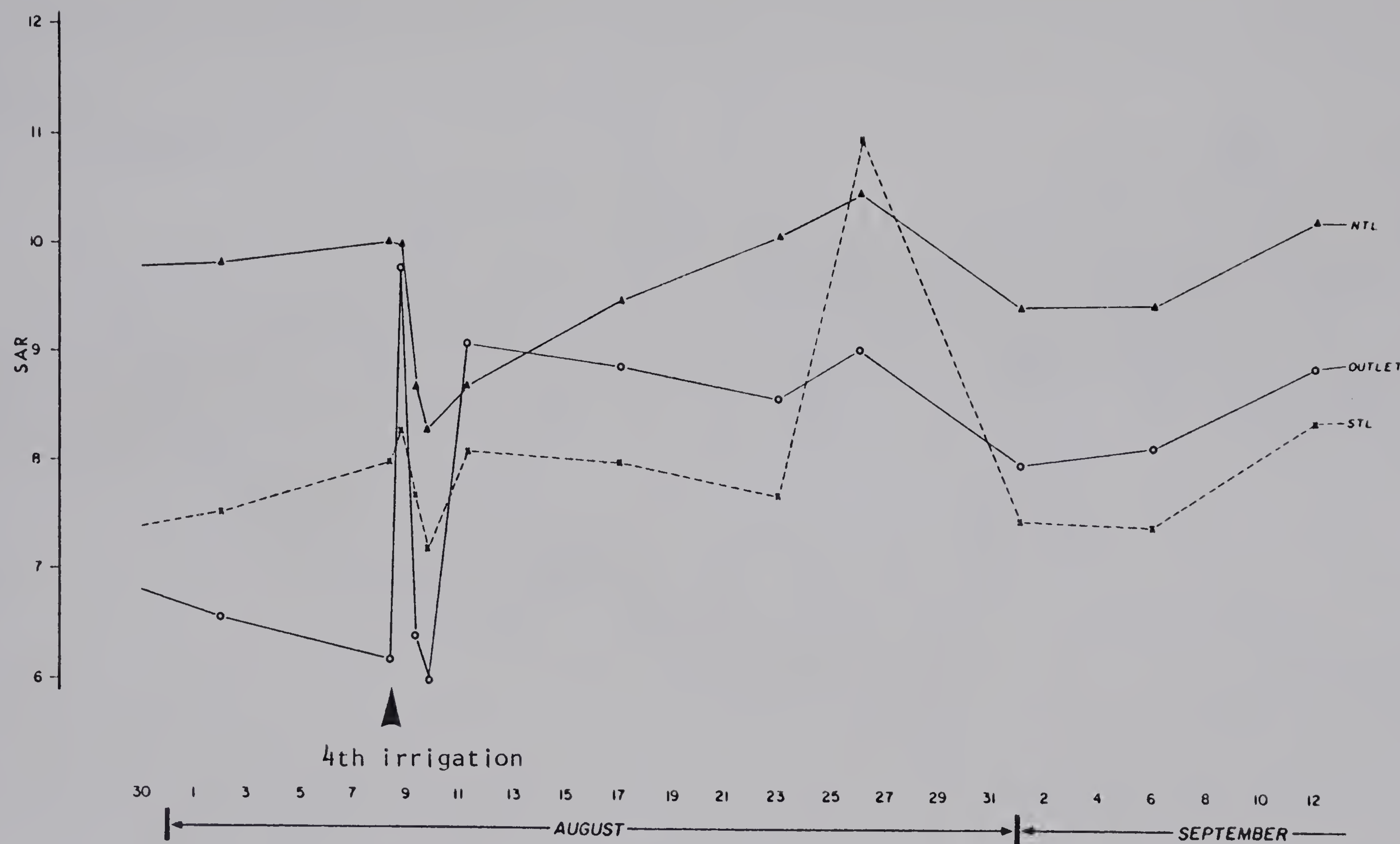
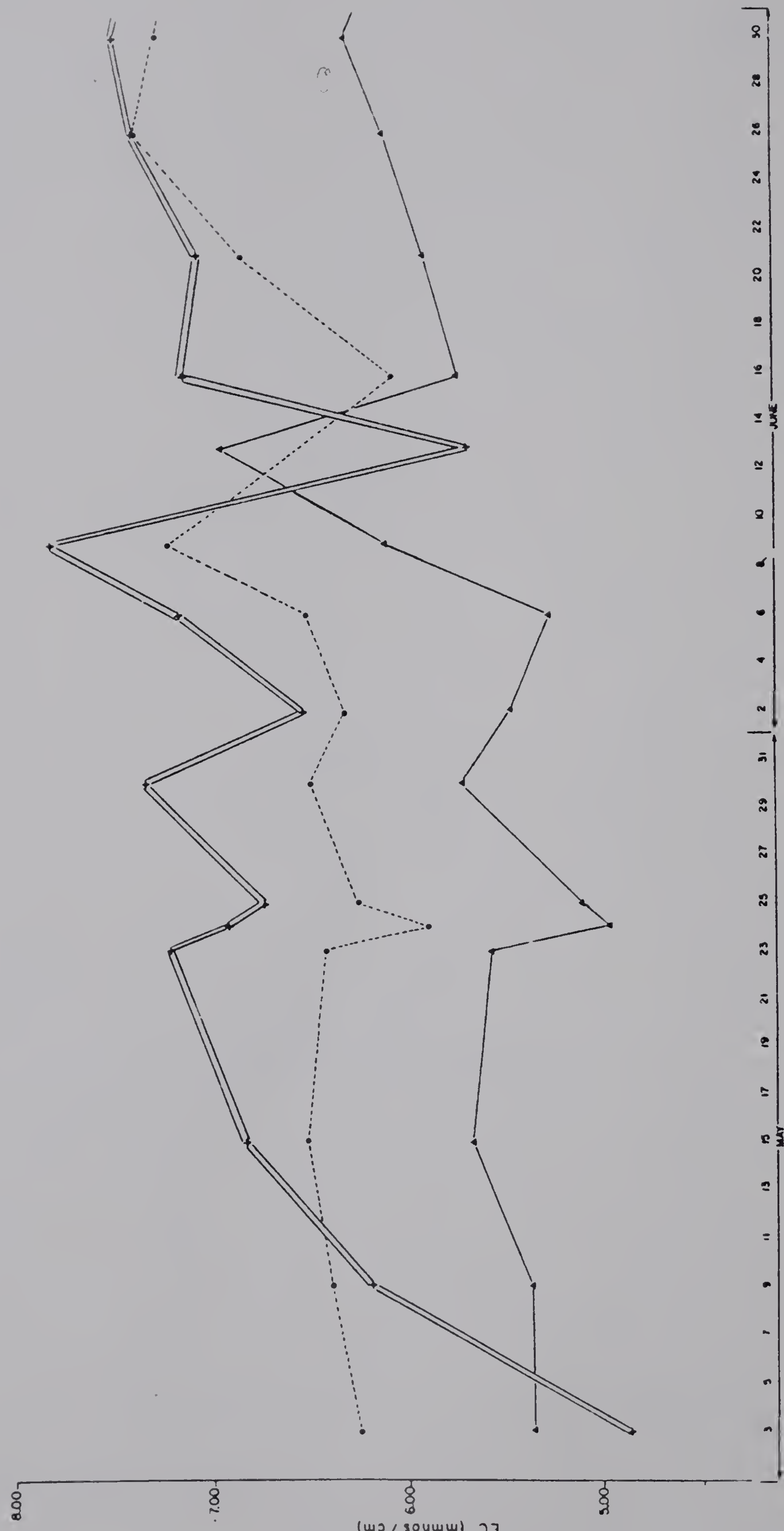


Figure 23. SAR of drainage effluent over 1977 growing season.


EC (mmhos / cm)
8.00
7.00
6.00
5.00
MAY
JUNE
3 5 7 9 11 13 15 17 19 21 23 25 27 29 31
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30

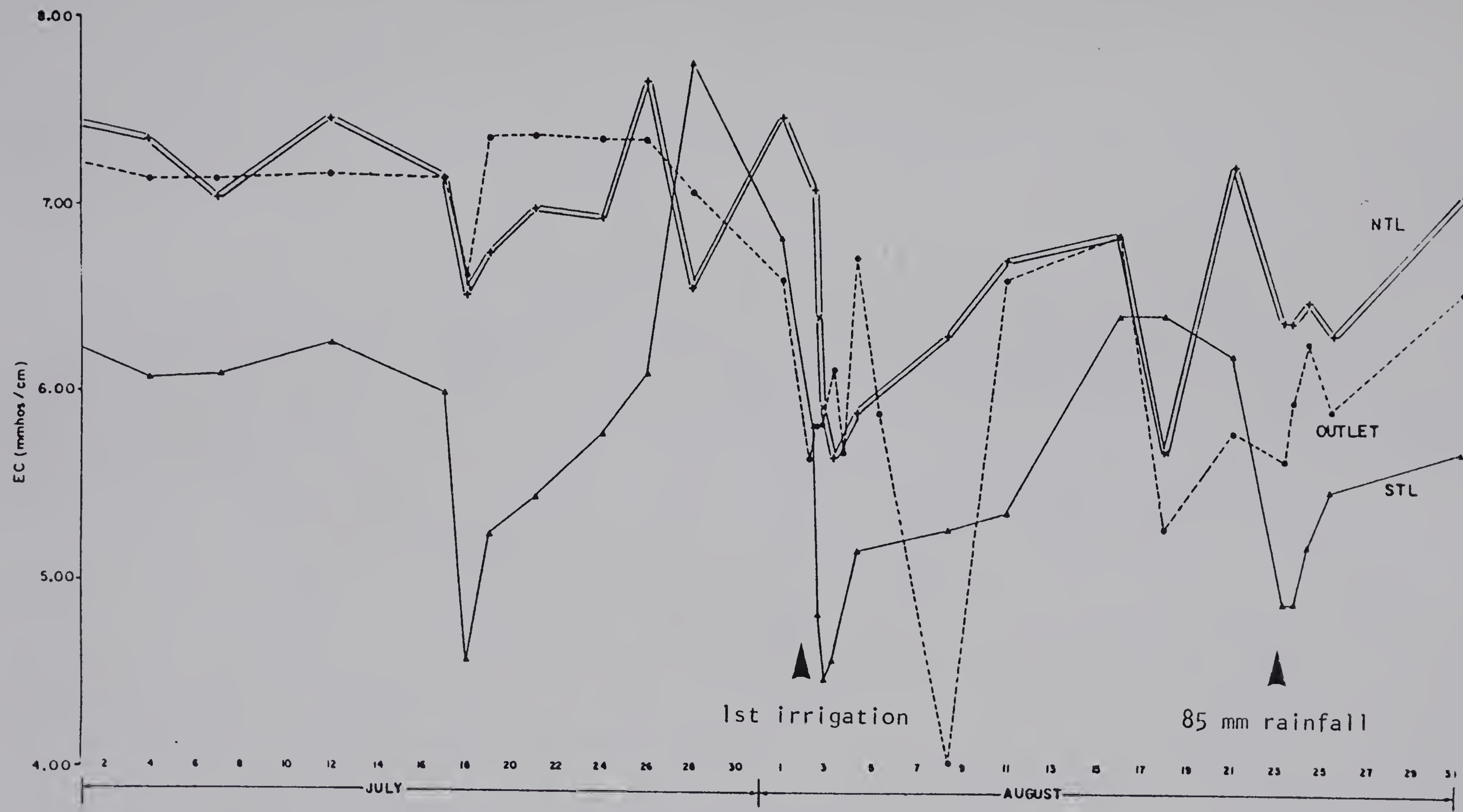
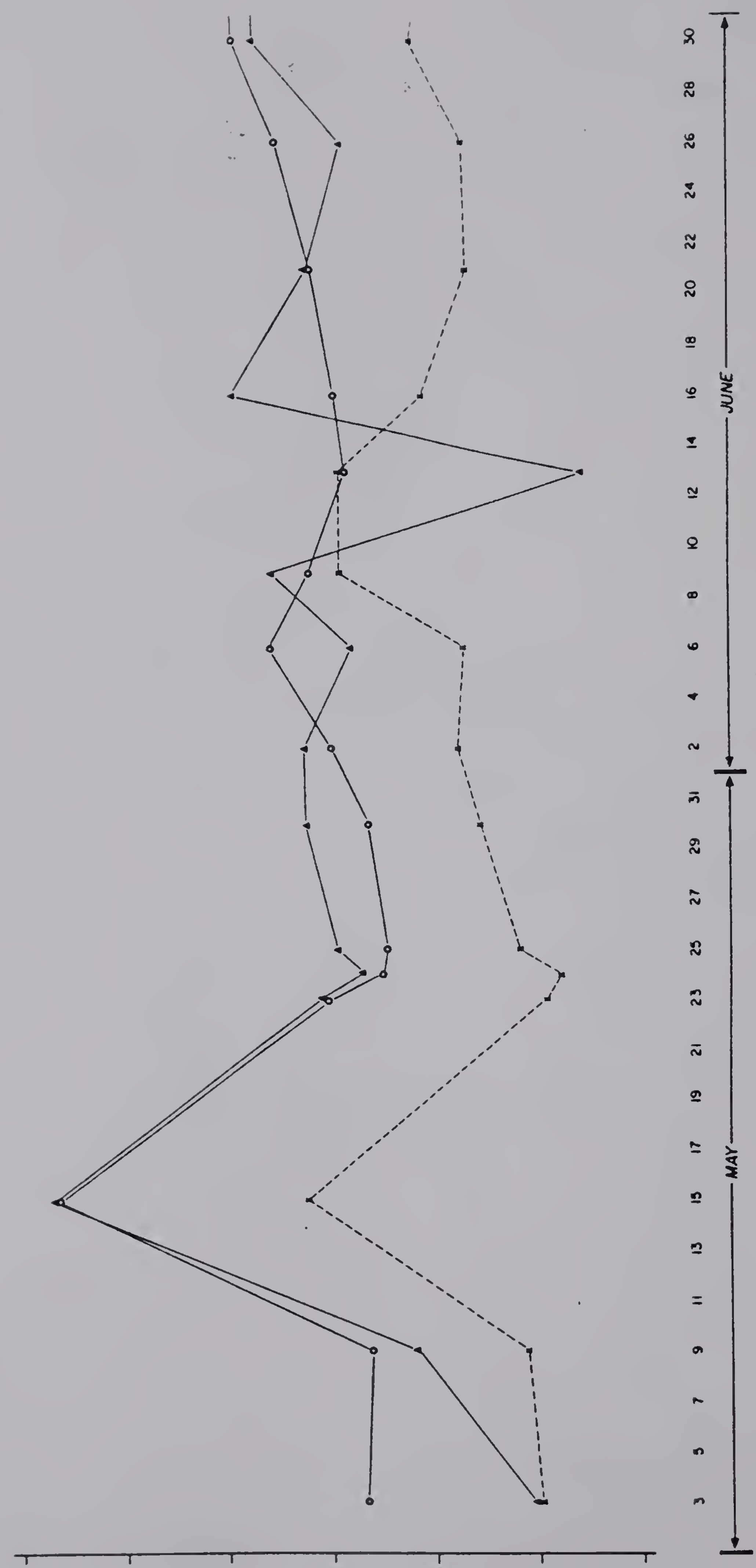


Figure 24. Electrical conductivity of drainage effluent over 1978 growing season.


SAR
12
11
10
9
8
7
6
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
MAY
JUNE

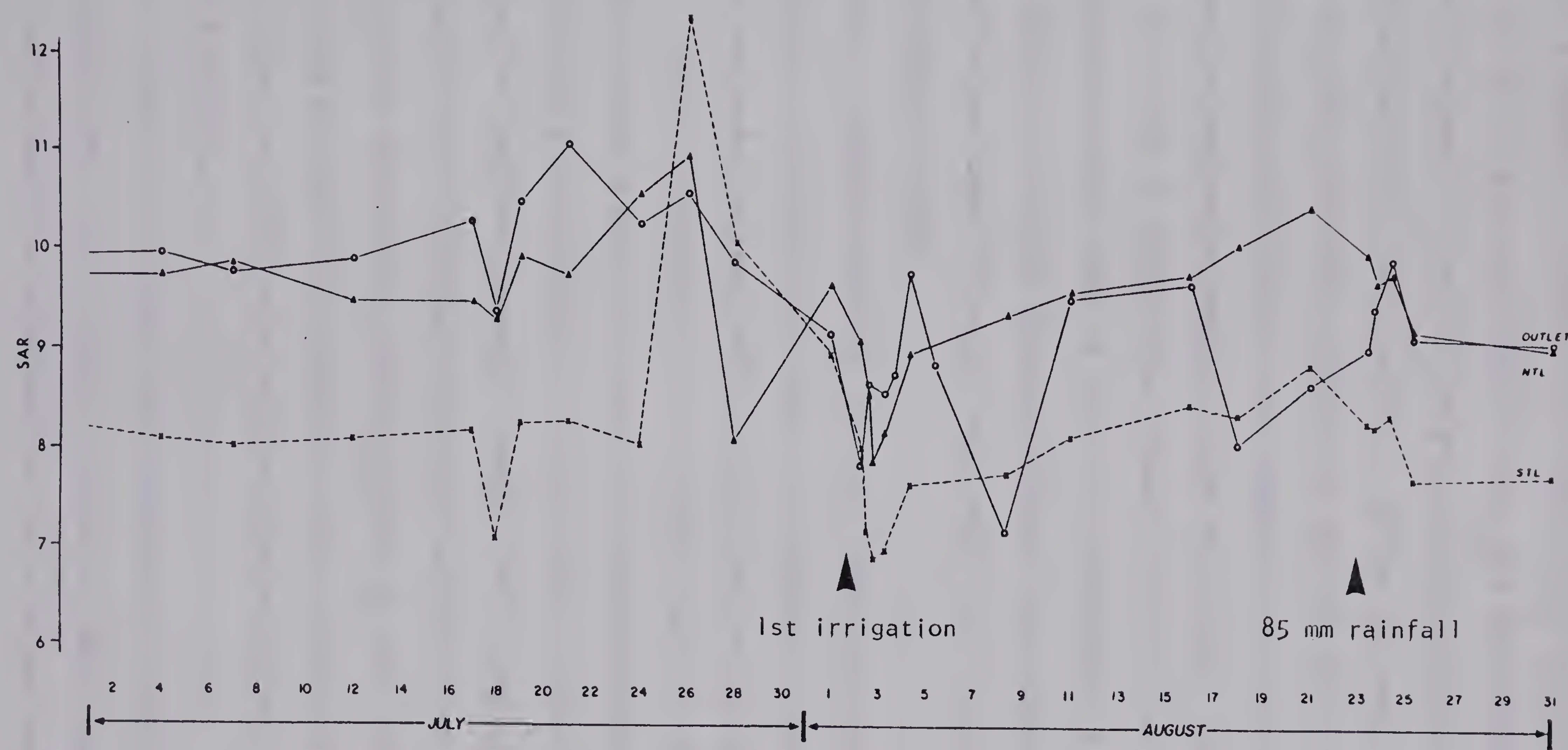


Figure 25. SAR of drainage effluent over 1978 growing season.

Major rainfalls occurred in 1978 on May 23 and 24 (31 mm); May 28 to 31 (28 mm); July 1 to 9 (51 mm); July 17 to 19 (57 mm); August 17 and 18 (34 mm) and August 21 to 23 (85 mm). Fluctuations of 1 to 2 units in EC or SAR were observed for most of these periods, especially May 23 and 24, July 17 to 19, and during the irrigation, August 1 to 3. A large improvement in the water quality from the outlet was observed on August 8 during the farmer's irrigation of an adjacent barley crop, some of which was underlain by the drainage system. No major dilution effect was observed near the end of August when 85 mm of rain were received in a relatively short period.

In 1977 a higher salinity (EC and SAR) was noted for effluents from the north tile line as compared to the south tile line and main outlet, with the latter two paralleling each other rather closely. The data point for the SAR of the south tile line on August 26 appears to be erroneous. The relative salinity of effluents from the tile lines to that from the outlet shifted somewhat during 1978. Effluent from the main outlet had comparable quality to that from the north tile line whereas the water quality of the south tile line was usually lower. The relative salinities of the north and south tile line effluents did not change to any appreciable degree.

Split Ca and Mg analyses were performed on effluent samples during 1978. Since $MgSO_4$ is more soluble than $CaSO_4$ the Ca:Mg ratio would be expected to increase as reclamation

took place. The results (data on file) indicated that the Ca:Mg ratio of the water remained constant throughout the growing season which implies that the site is being reclaimed very slowly, if at all.

The data for the major anions is not included here since significant trends were not observed. Data are on file with Alberta Environment, Lethbridge.

Soil Chemistry

Results from soil samples analyzed for EC and SAR are presented in Figures 26 through 33. Figures 26 to 29 depict the chemistry of soil profiles in the spring and fall of each year. The other four figures show the effect of the location of the tile lines on the dynamics of soil salts for 4 borders which were selected to illustrate the trends throughout the site. Similar samples were taken along 6 other border dykes. Analysis of these additional samples showed similar trends to the results presented here and are currently on file with Alberta Agriculture, Lethbridge.

A close look at the soil chemical profiles revealed that EC and SAR values were decreased substantially only for the 0 to 15 cm samples and sometimes for the 15 to 30 cm samples. The salinity of the remainder of the profile generally did not change very much and few, if any, trends were noticeable. Some locations even showed slight increases in salinity levels. Ballantyne (1978) also found that salt concentrations at some sites in dryland areas of

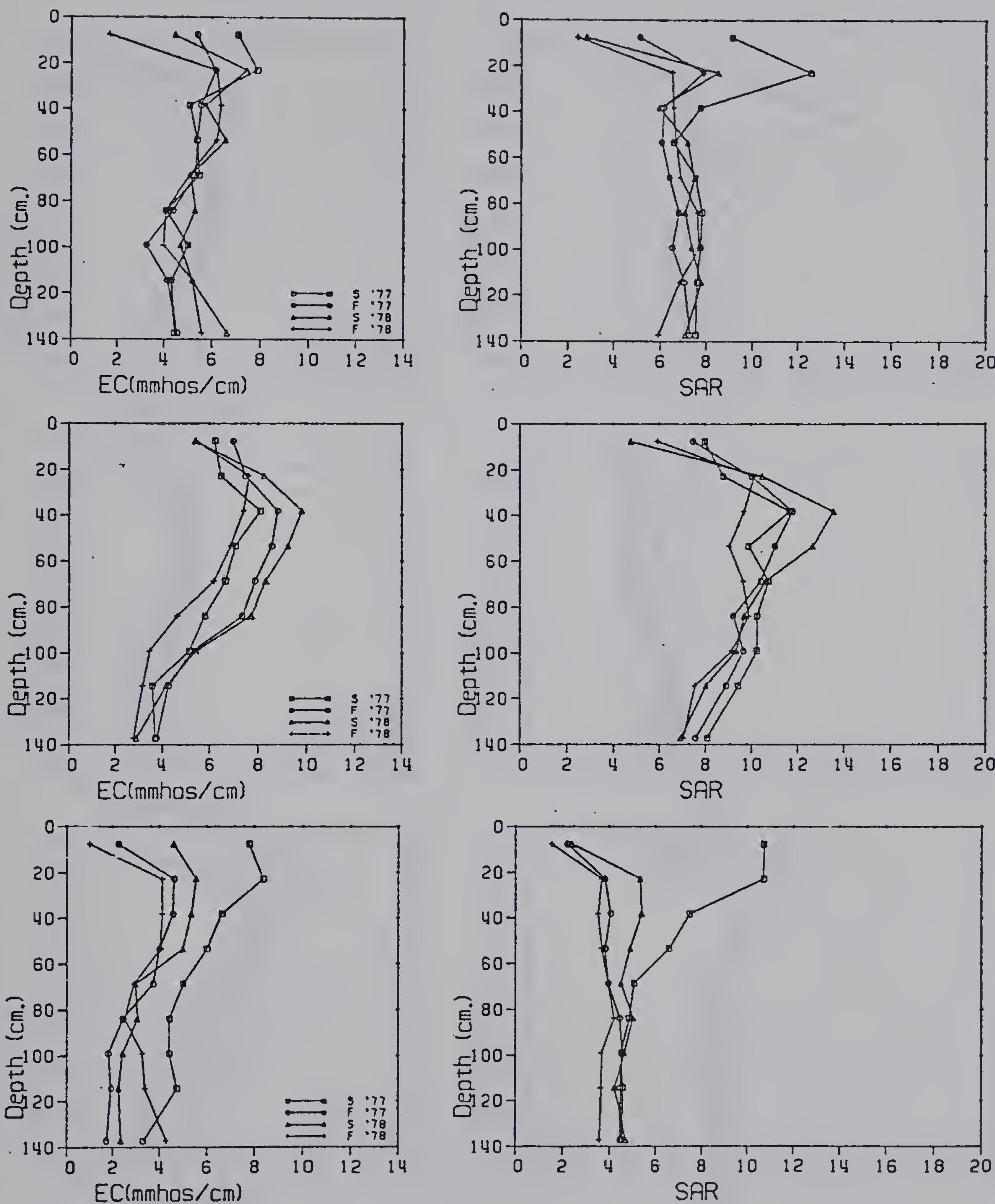


Figure 26. Soil chemical profiles from the midpoint of the 30 m spacing (top pair); over the tile line (center pair); and from the midpoint of the 15 m spacing (bottom pair) - F-8 East border.

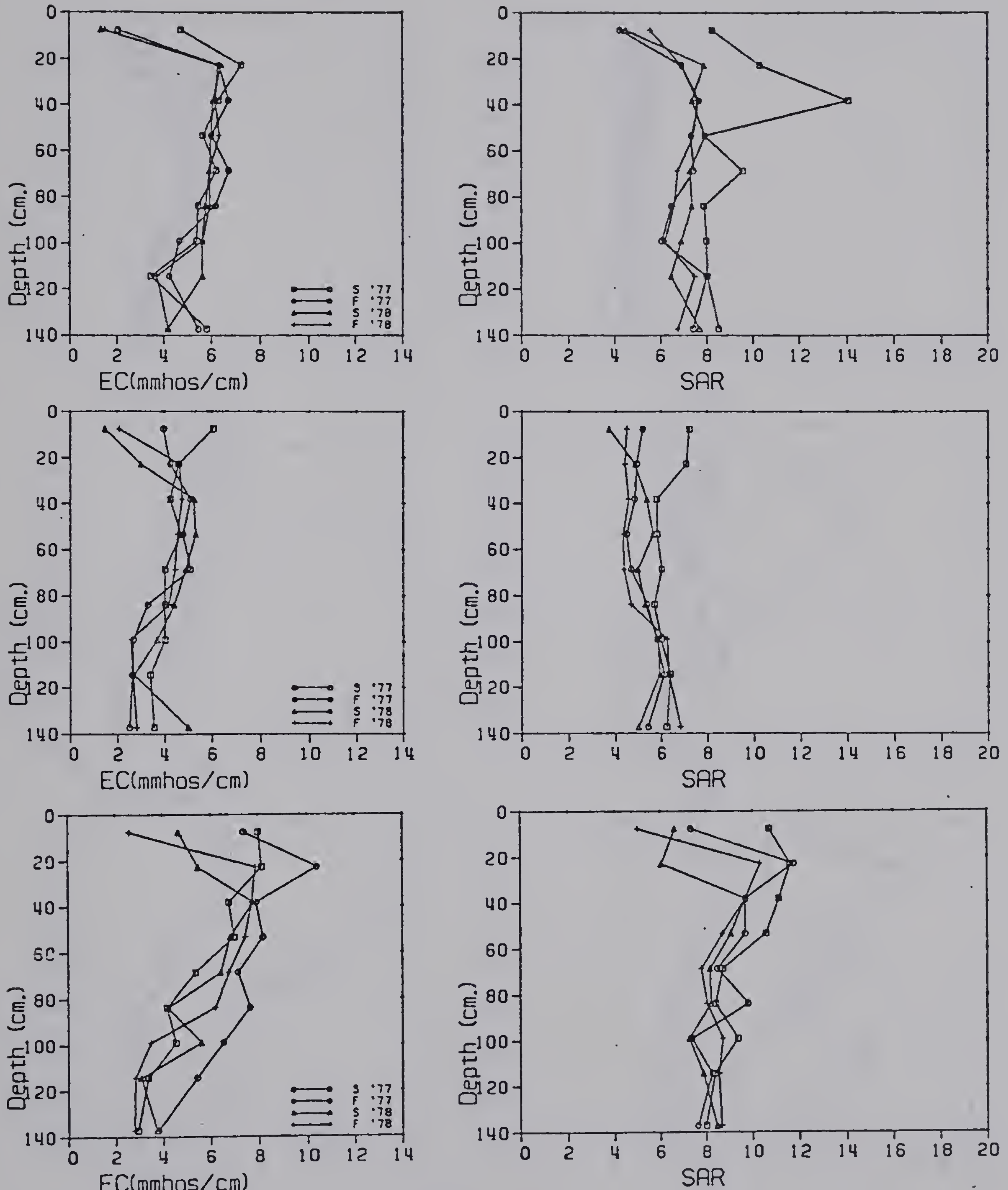


Figure 27. Soil chemical profiles from the midpoint of the 30 m spacing (top); over the tile line (center); and from the midpoint of the 15 m spacing (bottom) - E-8 West.

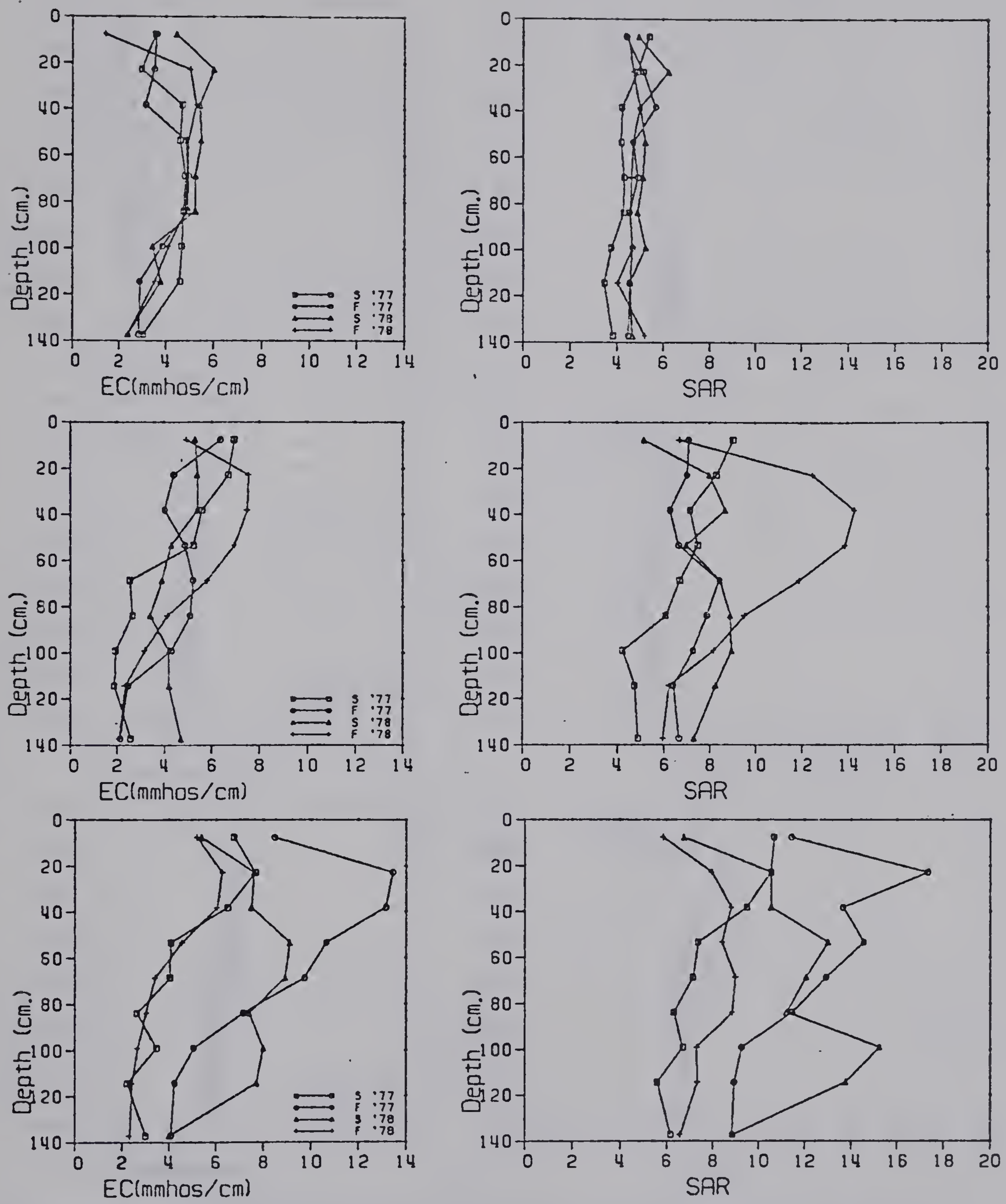


Figure 28. Soil chemical profiles from the midpoint of the 30 m spacing (top); over the tile line (center); and from the midpoint of the 15 m spacing (bottom) - C-8 East.

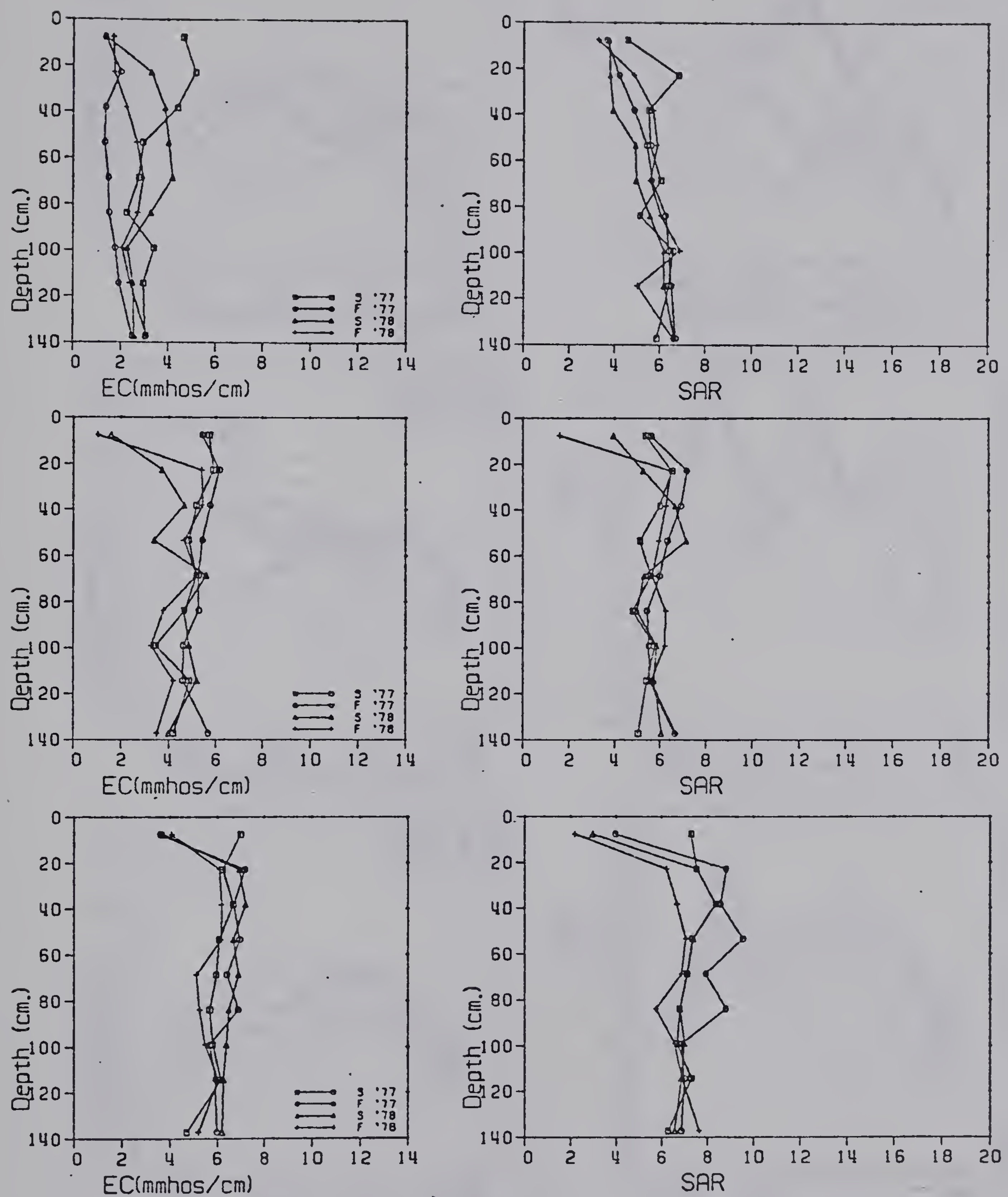


Figure 29. Soil chemical profiles from the midpoint of the 30 m spacing (top); over the tile line (center); and from the midpoint of the 15 m spacing (bottom) - B-8 West.

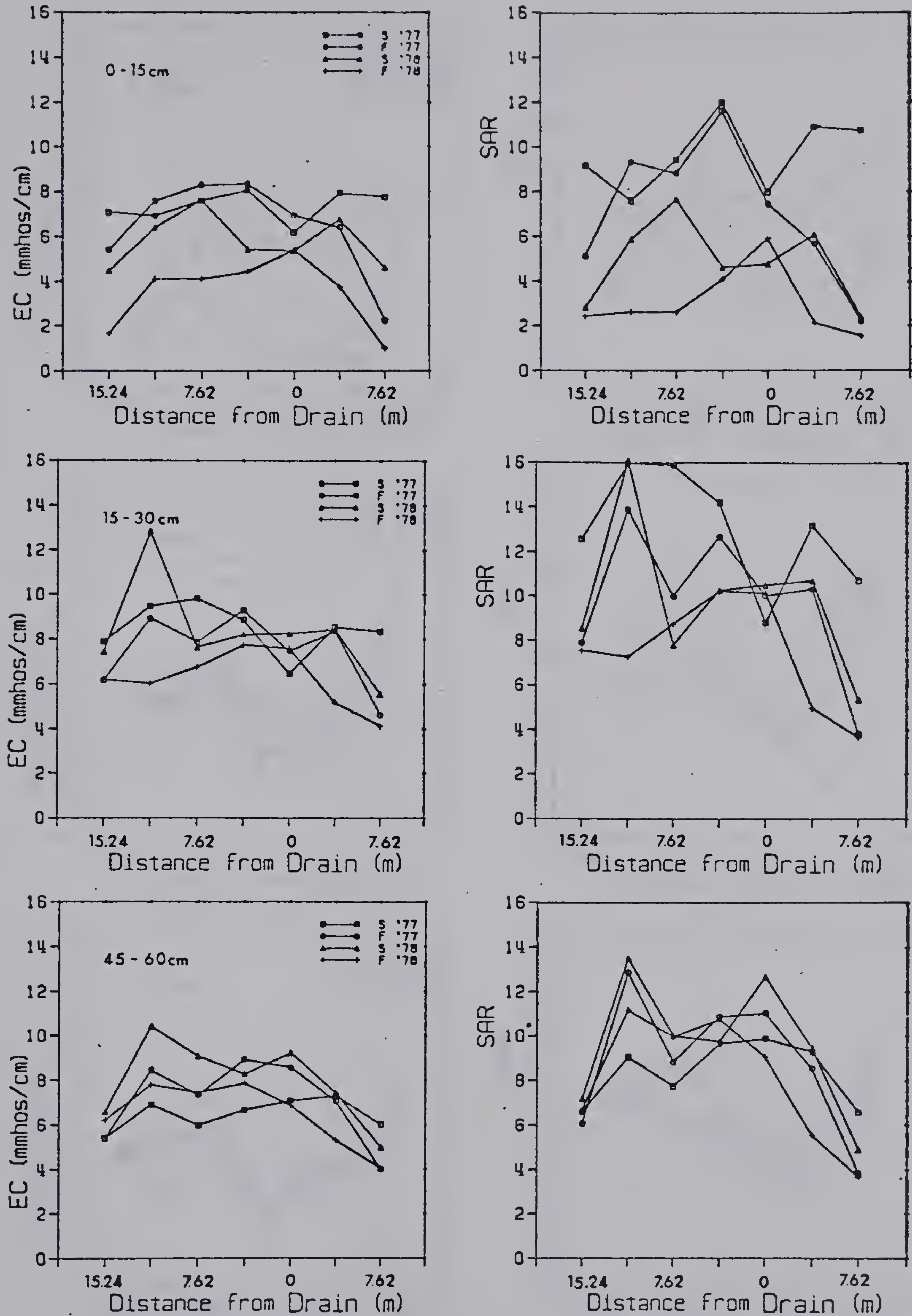


Figure 30. Soil chemical profiles in relation to location of tile lines for 3 depths - F-8 East.

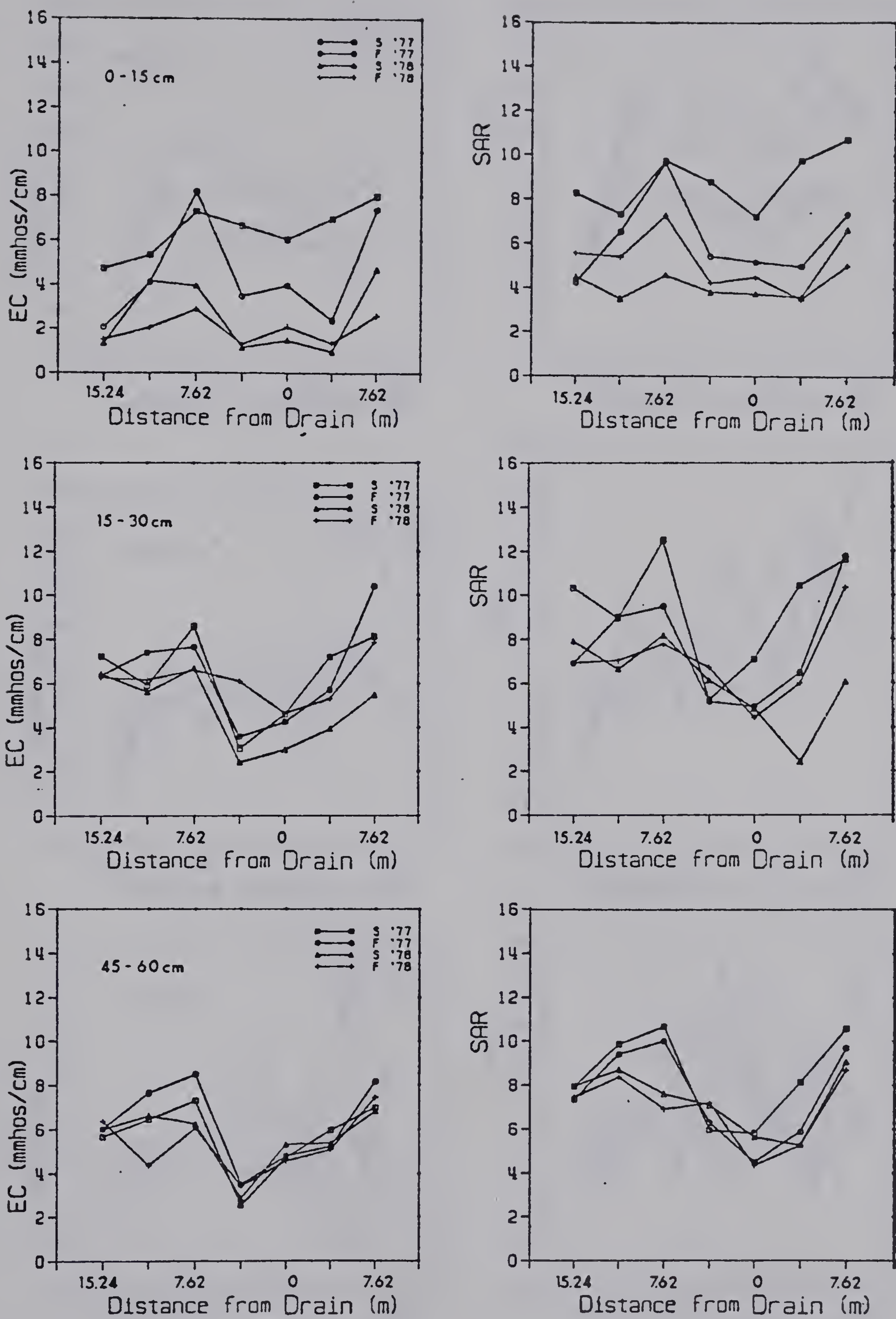


Figure 31. Soil chemical profiles in relation to location of tile lines for 3 depths - E-8 West.

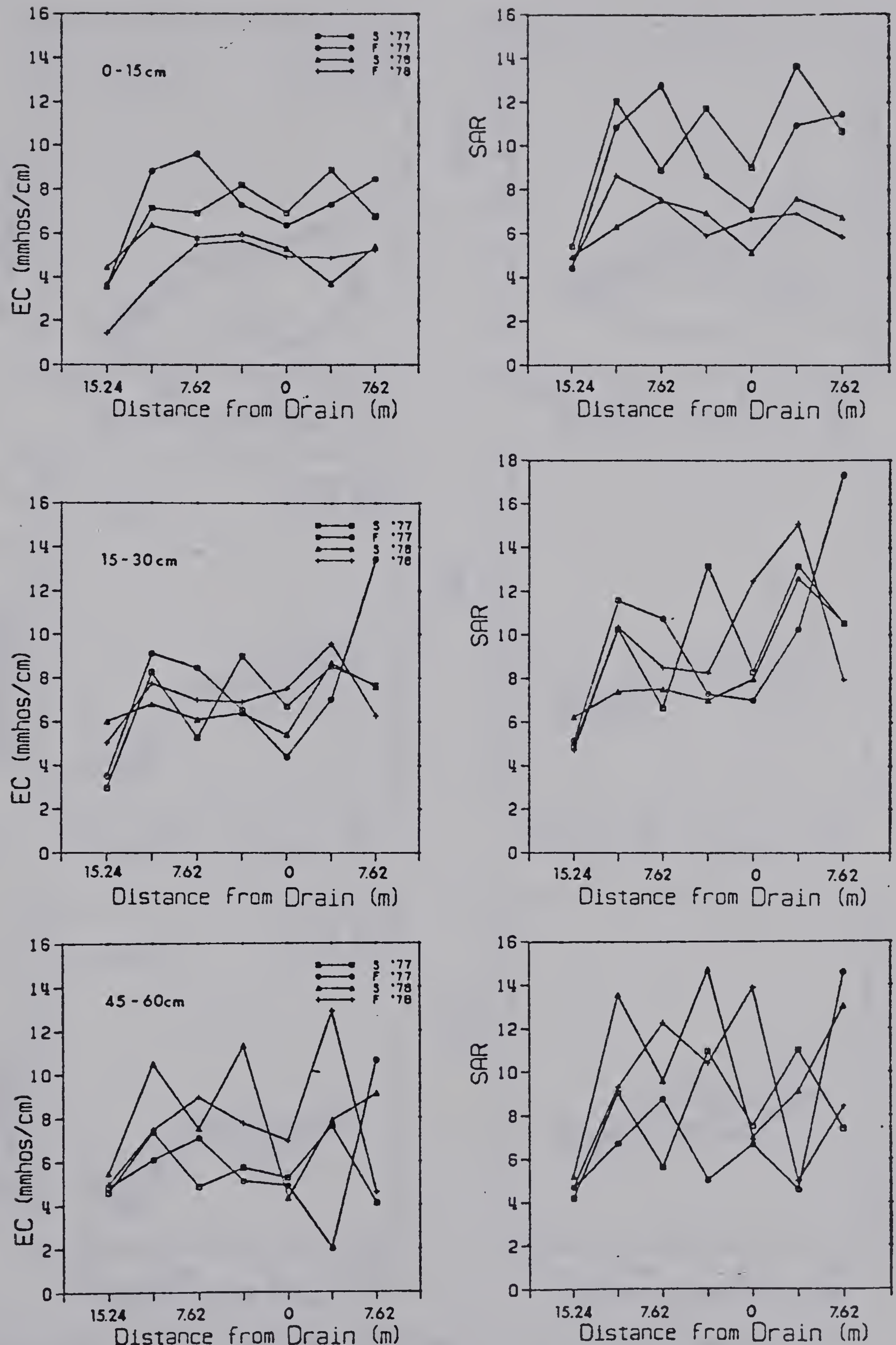


Figure 32. Soil chemical profiles in relation to location of tile lines for 3 depths - C-8 East.

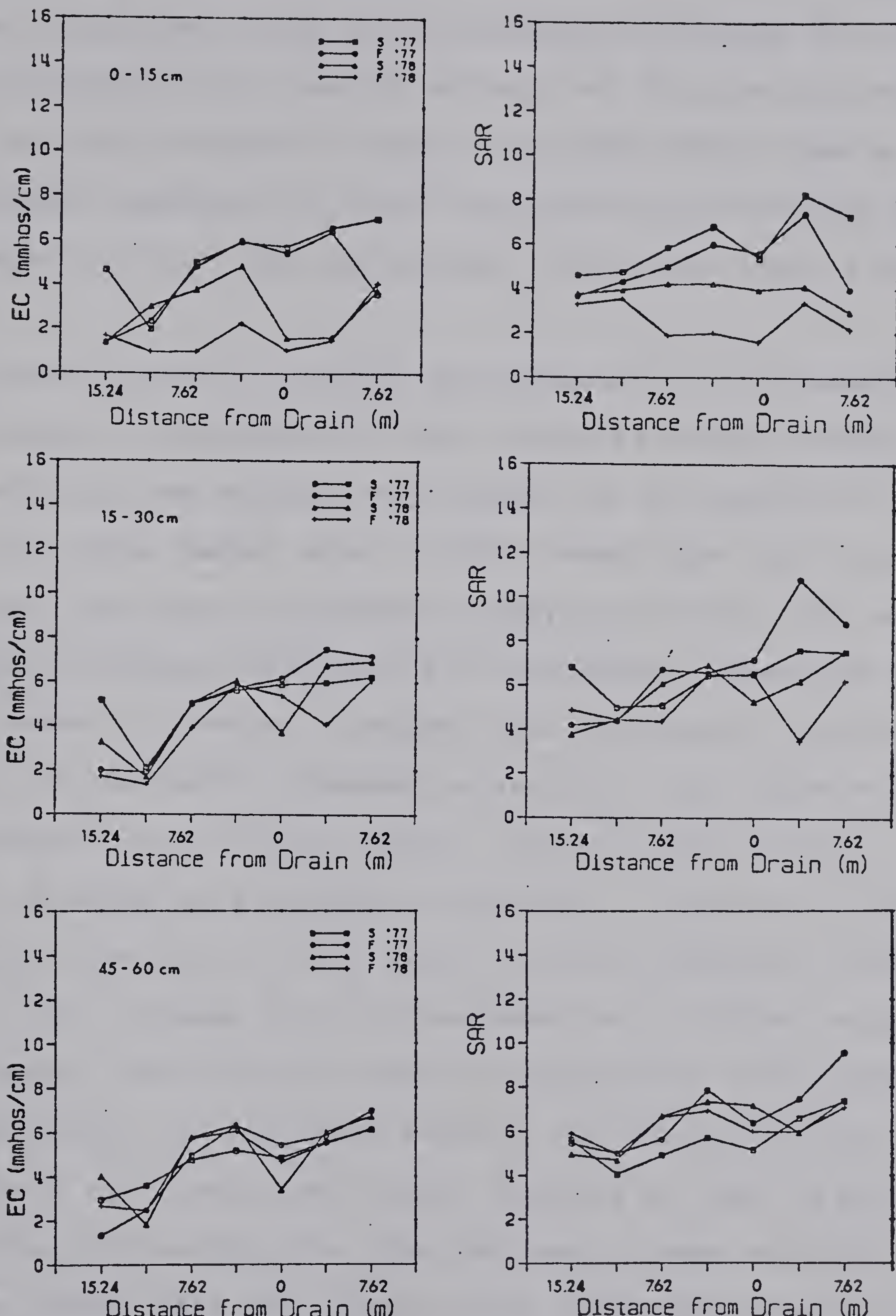


Figure 33. Soil chemical profiles in relation to location of tile lines for 3 depths - B-8 West.

Saskatchewan changed in opposite directions to the average change in the area. Many of the profiles in Figures 26 to 29 show significant increases in salinity at 30 to 60 cm, below which salinity remained constant. Christie (1968) found a significant reduction in total salts only in the surface 30 cm between January 1966 and October 1967 to the west of the site.

Figures 30 to 33 portray the changes in soil chemistry with respect to proximity to tile lines. No strong trends in soil salinity are evident with respect to the location of the tile lines. Sadler et al. (1965) showed that salt in the soil over the drain is removed largely by velocity flow and dispersion whereas diffusion is of increasing importance in salt removal at greater distances from the drains. Greater removal of salt with increased proximity to tile lines was not detected at the site; however, Vander Pluym and Kerr (1971) observed soil salinity reductions as increasing with increased proximity to tile lines for the interceptor drain to the west. Figures 30 to 33 represent only surface samples and samples taken from the depth corresponding to the bulge in soil salts. The decreased salinity of the soil in the surface 30 cm is expressed in the majority of these graphs regardless of the distance from the drain. These salinity changes within this soil appear to be intimately related to the apparently impermeable nature of the soil profile as discussed in the next section.

When this study was initiated large numbers of soil

samples were obtained to enable statistical methods to be used in evaluating the most effective depth and spacing to be used for drainage purposes. Careful examination of the soil chemical profiles, water quality, and the seemingly impermeable nature of the soil profile led to the decision that statistical analyses were not necessary inasmuch as soil salinity was decreased to an observable extent only within the surface 30 cm. The unusual behavior of the site during applications of water also influenced the decision to forego these statistical procedures.

D. Water Movement Through the Soil Profile

One of the most perplexing questions arising from a study of this drainage system involved the rapid response of the water table to applications of water. Such a response was quite unexpected considering the fine texture of the root zone soil material and its apparent extremely low hydraulic conductivity as determined by various standard tests. Several supplementary experiments were initiated in the latter part of the 1977 growing season and throughout the summer of 1978 to study the movement of water through the soil profile to the depth of the drains.

Tensiometers

Moisture fluctuations in the unsaturated zone are well represented in Figure 34 which shows that moisture tension changes were most dramatic at 15 cm with the tensiometer at 30 cm showing a similar, but less dramatic, response. The moisture tension at 60 and 90 cm depths did not significantly change and remained quite low over a prolonged period. An upward gradient observed between applications of water may have contributed to accumulations of salts below 30 cm through capillary rise and subsequent evaporation of water. The influence of applications of water on soil moisture is clearly depicted on August 2 and 3 and 23 and 24. The observation that tensions on August 2 and 3 were not reduced to zero may be related to the time when readings were taken and to the lag time of the tensiometers. Tensions may well have reached zero at some time during the irrigation period. The soil near the surface would be expected to dry out more rapidly and it is interesting to note that the zone of maximum fluctuation (0 to 30 cm) corresponds to that portion of the soil profile where greatest reductions in soil salinity occurred.

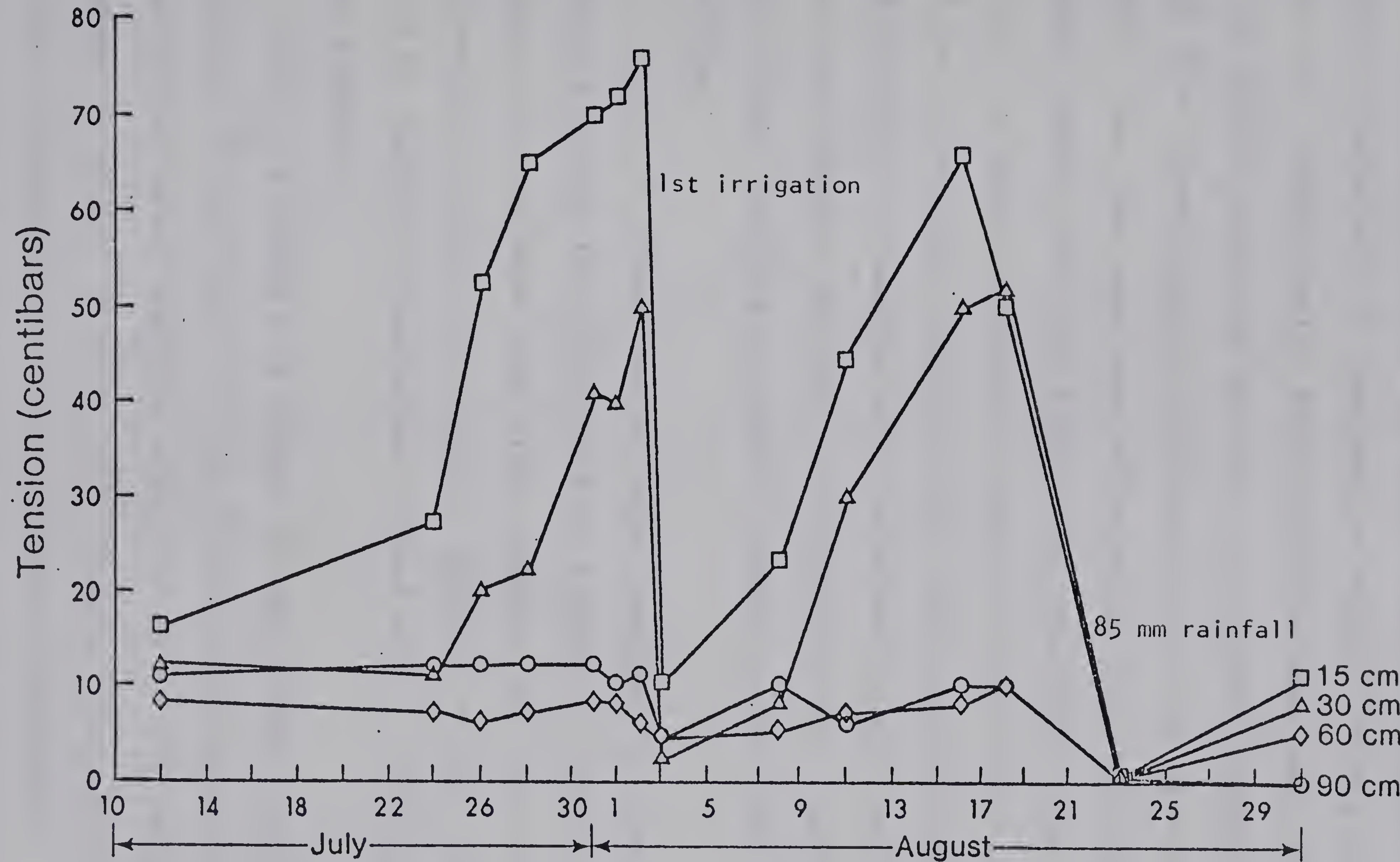


Figure 34. Moisture status of soil according to tensiometers at various depths -- 1978.

<u>Suction Lysimeters</u>

The quality of several water samples obtained from suction lysimeters is depicted in Figures 35 and 36 for 1977 and 1978, respectively. These profiles show salt bulges near 60 cm depths which may be due to the downward movement of salt from above. The low permeability of the fine textured soil in the root zone was reflected in the time required to obtain samples from the lysimeters, especially the lysimeter at a 75 cm depth. Between irrigations the water table was at a 1 to 1.2 m depth, therefore the lower samples represent the salinity of samples under saturated conditions whereas the other samples reflect the salinity of the unsaturated zone. These profiles are quite similar to the soil chemical profiles.

Figure 35 shows that no major changes in water quality occurred during the irrigation on August 9, shortly after (August 11) and some time after (August 17). The water table was near the surface on August 9 (within 15 cm), receded to 80 cm by sampling time August 11 and was at approximately 1 m on August 17.

The 1978 samples in Figure 36 show higher salinity levels at 30 cm than at 45 cm. This may be explained by the rise of the water table to within 50 cm of the surface as opposed to within 15 cm in 1977. Samples were not collected on July 12 (before irrigation) from the shallower lysimeters. Generally, increased salinity was observed for all profiles 5 days following irrigation as indicated by

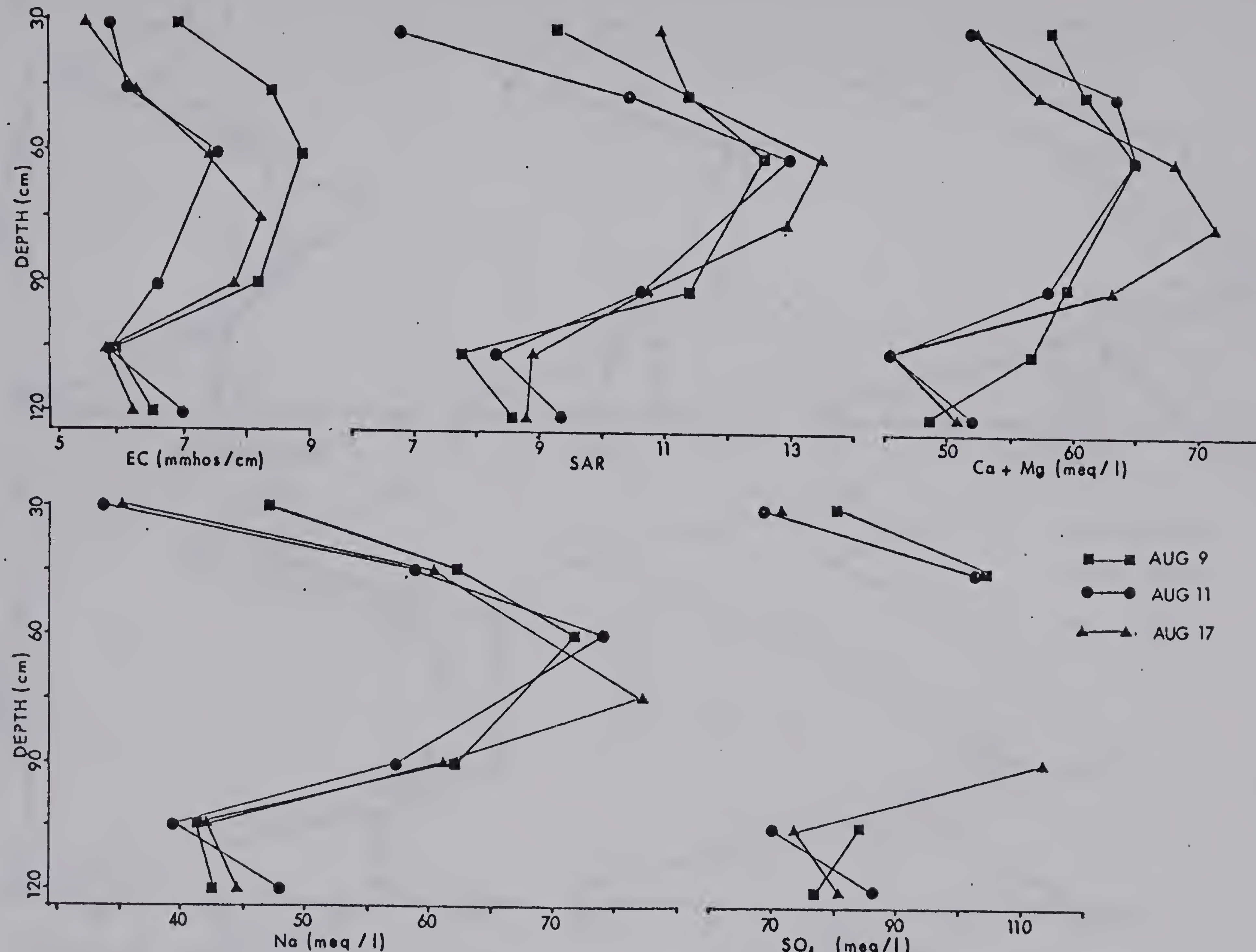


Figure 35. Chemical profiles of samples from suction lysimeters - 1977.

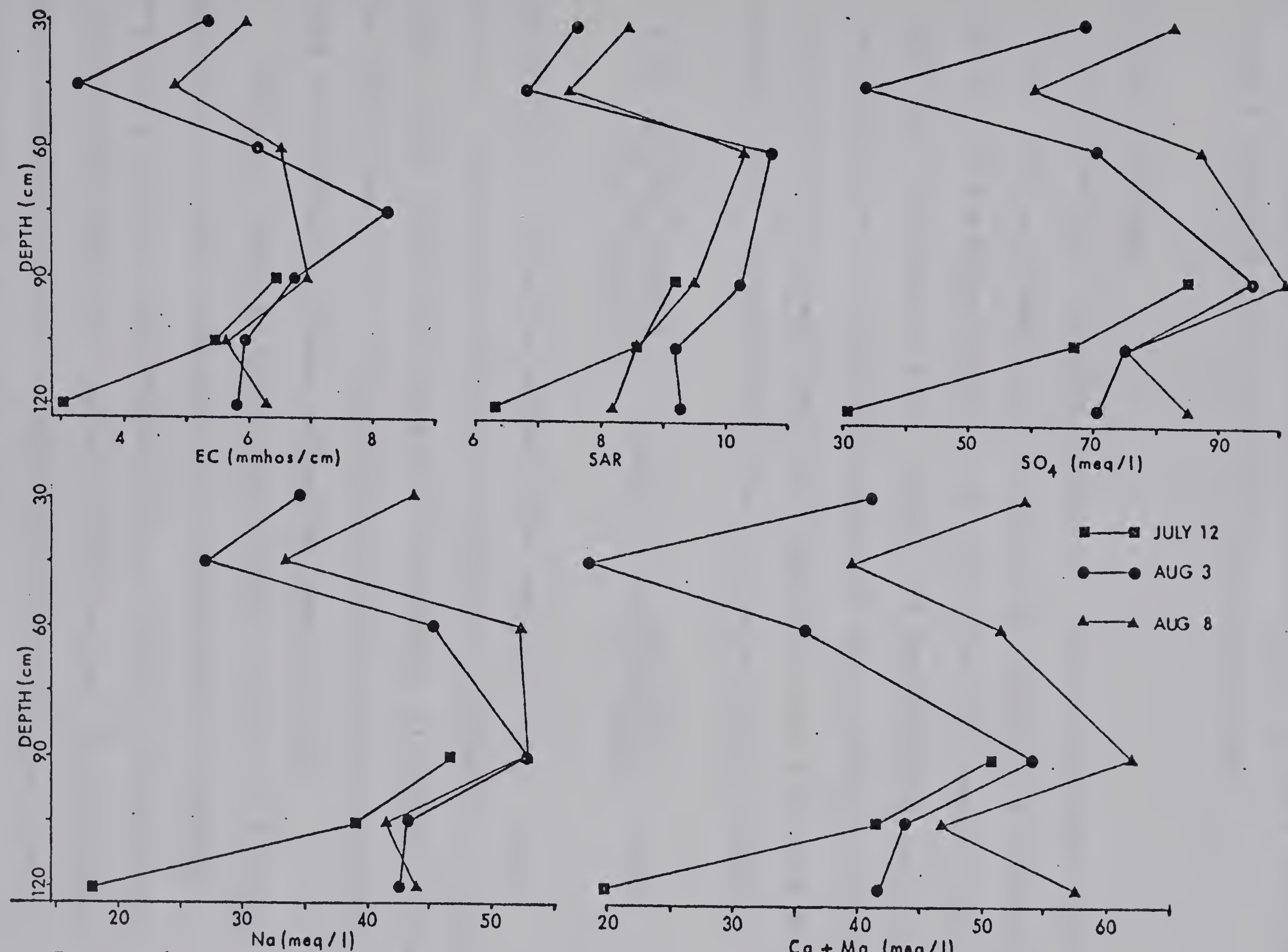


Figure 36. Chemical profiles of samples from suction lysimeters - 1978.

samples collected on August 8. This may reflect the concentrating effect of evapotranspiration on soil salinity as soil moisture was lost following irrigation.

Natural Isotopes

The natural isotopes oxygen-18 (^{18}O), deuterium (D) and tritium (T) were used to determine the source and relative age of the drainage effluent at the site. The results are tabulated in Table 13 for a light (31 mm) rainfall and the one irrigation in 1978. The oxygen-18 and deuterium numbers are expressed in parts per mille (‰) with the $\delta^{18}O$ and δD numbers being obtained from the following relationships:

$$\delta^{18}O = \left(\frac{^{18}O/^{16}O \text{ sample}}{^{18}O/^{16}O \text{ standard}} - 1\right)1000; \quad \delta D = \left(\frac{D/H \text{ sample}}{D/H \text{ standard}} - 1\right)1000$$

The standard water is called SMOW (standard mean ocean water). The concentration of tritium is expressed in tritium units (TUs) which correspond to the number of tritium atoms per 10^{18} atoms of H. Oxygen-18 and deuterium are primarily used to determine source areas for groundwaters.

Bouwer (1978) explains that large amounts of tritium were added to the atmosphere by thermonuclear activity beginning around 1954. Thermonuclear tritium entered the hydrological cycle and caused the TU values of atmospheric precipitation to vary considerably. Peak tritium levels of precipitation in the Northern Hemisphere were reached in 1963-1964, after which a ban on atmospheric thermonuclear

Table 13. Oxygen-18, deuterium and tritium concentration of water samples.

	δ^{18}Osmow (‰)	δDsmow (‰)	T.U.
Rainfall samples (May 23 & 24)			
Drainage effluent			
- prior to rainfall	-17.3	-131	141 ± 12
- high discharge	-17.2	-129	140 ± 12
- low discharge	-17.2	-131	144 ± 12
2 m piezometer	-16.9	-134	100 ± 17
4 m piezometer	-17.5	-129	122 ± 17
Precipitation	-12.6	- 90	181 ± 17
Irrigation samples (Aug. 1 to 3)			
Irrigation water	-16.0	-117	67 ± 11
Drainage effluent			
- prior to irrigation	-16.8	-127	103 ± 12
- increasing discharge	-16.4	-121	87 ± 11
- high discharge	-15.6	-113	86 ± 11
- decreasing discharge	-16.4	-121	67 ± 11
- post-irrigation	-16.8	-125	70 ± 11
Tile line effluent			
- prior to irrigation	-16.4	-128	100 ± 11
- high discharge	-16.7	-121	123 ± 12
- low discharge	-17.3	-129	87 ± 11
1.75 m piezometer			
- prior to irrigation	-16.9	-128	102 ± 11
- high water table	-16.7	-126	118 ± 11
- low water table	-16.9	-127	80 ± 11
2.0 m piezometer			
- prior to irrigation	-16.9	-128	103 ± 12
- high water table	-17.0	-127	87 ± 11
- low water table	-16.6	-117	69 ± 11
4.0 m piezometer			
- prior to irrigation	-17.4	-136	75 ± 11
- high water table	-18.3	-131	62 ± 11
- low water table	-17.4	-126	60 ± 10
Piezometer in bedrock	-20.1	-148	-5 ± 10
Piezometer in till above bedrock	-19.9	-143	+6 ± 10

testing led to a decline in TU values. Comparison of the tritium levels in groundwater and rainfall enables determination of the apparent age of the groundwater. Groundwaters containing no tritium are interpreted as having entered the flow system before 1954. High tritium levels imply recharge during the period of intensive thermonuclear testing (1954-1965). The tritium concentration of groundwater and precipitation varies annually and seasonally (highest summer, lowest winter) and is also affected by radioactive decay and mixing within the flow system.

Examination of the tritium data in Table 13 indicates that samples taken from the piezometers in the bedrock and from the overlying till are "dead" water or water which entered the flow system prior to 1954. All of the other samples are relatively young which implies that this water entered the flow system within the last 5 to 10 years.

Interpretation of the oxygen-18 and deuterium data was facilitated by plotting them in Figure 37. When the isotope concentrations of precipitation from the various parts of the Northern Hemisphere are plotted, a straight line with the equation $\delta D = 8\delta^{18}O + 11$ can be drawn (Dansgaard, 1964). This is known as the meteoric water line (MWL). Evaporation of water from open water bodies leads to enrichment in the heavier isotopes, oxygen-18 and deuterium, because the various forms of water have different vapor pressures (Dincer, 1968). The relationship of the isotopes thus departs from the MWL under evaporitic conditions.

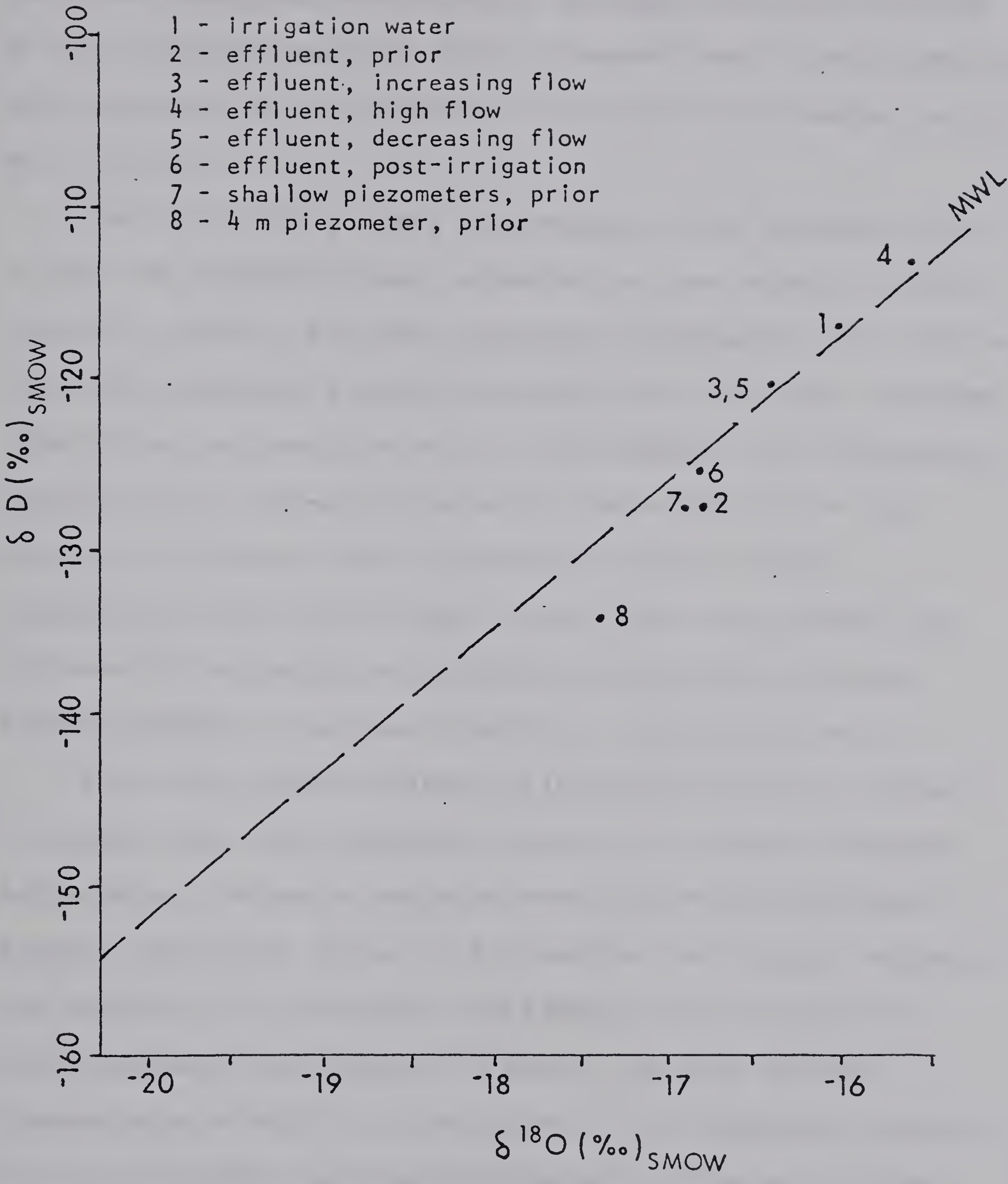


Figure 37. Position of isotope samples along MWL showing the effect of irrigation water.

The source of the drainage effluent was an important question requiring consideration because the water quality of the effluent remained fairly constant and corresponded to water quality of the groundwater (EC of 5 to 8 mmhos/cm; SAR of 7 to 10).

The preliminary study involving a 31 mm rainfall (May 23 and 24) indicated that rainwater was not moving through the soil profile. The most plausible explanation for this is that this moisture was stored within the root zone. Samples taken from shallow piezometers had oxygen-18 and deuterium concentrations which corresponded quite closely to the drainage effluent. This is expected between water applications but the isotope values would be expected to increase if rainwater was actually percolating through during periods of maximum discharge (3.0 liters/sec).

The water samples taken during the irrigation period indicated that the irrigation water and drainage effluent had similar O^{18} and D contents even when tile discharge volumes increased. Prior to irrigation the isotope values of the effluent, for both the individual tile line and the whole system, corresponded to values for the shallow piezometers. A shift in the oxygen-18 and deuterium values during irrigation is clearly depicted in Figure 37 which shows the relationship of these data to the MWL. The samples all fall near the MWL and shifts along the line are observed during the irrigation cycle. Maximum discharge rates during the irrigation period were 11.4 liters/sec. Prior to

irrigation the effluent and shallow piezometers had similar isotope content. During irrigation the effluent and irrigation water had similar isotope values. These trends may be used to designate the source of the effluent before and during irrigation periods but such a conclusion is complicated by other observations which will be discussed in the next section.

Concluding Remarks on Water Movement

The rapid response of the water table and the apparent low hydraulic conductivity of the soil profile created a number of questions as to whether or not water applied through irrigation or rainfall actually moved through the soil overlying the drains. Water levels in water table wells and piezometers started to increase within 3 to 4 hours after the application of water and receded to pre-irrigation levels within a couple of days. Calculated values of K (Tables 5 and 8) indicated that much longer periods of time would have elapsed before a response in the water table would be anticipated. Discharge from the drainage system paralleled the response of the water table, therefore it seems reasonable to assume that water was being supplied to the coarse layer from above during irrigations or heavy rainfall. The dilution effect observed in water quality of effluent also supports the concept that water moved through the root zone. The low amount of runoff and the similarity of the isotope (^{18}O, D) concentrations of the irrigation

water and drainage effluent also support this hypothesis. Observations which cast doubt on this idea are the low infiltration rates (Tables 4 and 7) and the 3 shallow (1 m) piezometers which remained dry throughout the irrigation in 1978 when water levels were measured to within 30 cm of the surface.

Ritchie et al. (1972) described the difficulty encountered in obtaining representative K values from undisturbed cores and disturbed soil samples. They found that cores were greatly affected by heterogeneities caused by cracks, rootholes and wormholes and were subject to edge effects or other disturbances. Hydraulic conductivity measurements on approximately 10,000 soil cores from 900 sites and 7 states yielded variations that were so great that K values from 5 cores at any site could be categorized as slow, moderate, or fast, with a 95% probability of being correct (Mason et al., 1957). When sample size was increased from 70 cm to 10 m in diameter, the measured K value for a swelling clay soil was increased from 0.3 to 2.5 cm/day (Ritchie et al., 1972). Van Schilfgaarde (1970) concluded that laboratory K values are usually "meaningless" for agricultural drainage problems. Our results tend to confirm this. In the literature fine-textured soils are reported to have K values in the order of 1×10^{-3} to 1×10^{-7} cm/sec (Cedergren, 1967).

Dixon and Weed (1977) state that water movement in soils high in smectites occurs mainly through large cracks

and voids. Ritchie et al. (1972) explain that structural unit boundaries, shrinkage cracks, and other heterogeneities provide pathways for water movement which are not detected in small cores. Bolt and Bruggenwert (1976) also discuss the phenomenon known as hydrodynamic dispersion wherein water ponded at the surface does not readily move through smaller pores but rather through larger voids or channels. Bouwer (1969) reported that the fraction of irrigation water that passes unchanged through larger voids and cracks was about 0.2 for fine-textured soils. The flocculating effect of high salt content may also contribute to increased soil permeability (Dixon and Weed, 1977). Therefore water could possibly move through the soil profile even if the aforementioned K values are realistic.

Another explanation for the rapid fluctuation of the water table is that the 70 water table wells throughout the site were acting as piezometers wherein the portion of the well within the coarse layer was sealed off from above by the relatively impermeable material from 60 to 120 cm. If such a phenomenon actually occurred, "false" water table levels may have been measured during periods of irrigation. Miller and Bunger (1963) found that the moisture content of a sandy loam soil underlain by sand or gravel increased as the coarse layer was approached. The rise of water in the water table wells may be due to a "piston" effect wherein air pressure which builds up below the wetting front forces water from the lower portion of the root zone into the

gravel layer (Nielsen et al., 1972). The low amount of available pore space (15% by volume) when the soil is at 50% of field capacity (assuming Db of 1.5) may result in displacement of water from the soil profile during irrigation. This hypothesis does not account for the relatively small amount of runoff which occurred during irrigation periods as compared to the quantity of water applied. The 400 to 600 m^3 of water applied was sufficient to provide a leaching fraction (0.2 to 0.5) which would be expected to eventually reach the coarse layer in the profile.

Evidence such as the relatively low amount of runoff, similar ^{18}O and D content of effluent and irrigation water during periods of water application, and low available pore space within this fine-textured soil, strongly suggest that water is able to move through the soil profile. A conclusion as to which hypothesis is correct is pending until further investigation clarifies the issue. The soil moisture data (especially Table A of Appendix 2) indicate that soil moisture content approached saturation (assuming Db of 1.5) to depths of 60 cm shortly after an irrigation. Further research should be done to monitor the wetting front during irrigation to the depth of the coarse layer. A neutron probe and gravimetric sampling may be useful for this purpose. The high Db of the soil profile must be considered when determining the available pore space of this fine-textured soil. Pressure transducers used in conjunction with

piezometers may also simplify investigation as to how the water table responded so quickly.

E. Crop Yield

The very dry moisture conditions into which the crop was seeded, coupled with the severe structure deterioration resulting from extensive land-forming operations, resulted in extremely uneven germination and emergence in 1977. Crusting was a severe problem after the first irrigation and necessitated harrowing of the sparse plant population. An adjacent part of the field underlain by the drainage tubing contained a crop of volunteer barley which the farmer deemed a better risk than the crop seeded into dry soil. Plant growth and vigor were extremely variable throughout the study area with some plants entering the boot stage while others were just emerging. A crop stand count representing the average of 40 sites yielded 77 plants per square meter. Crusting was evident throughout the growing season between irrigations but was not as severe as after the first irrigation. The volunteer barley crop was harvested the first week in August and the seeded barley in mid-September. Results for grain yields on 70 sampling sites are presented in Table A of Appendix 5. Grain yield amounted to an average of 1310 kg/ha. Analysis of variance of this randomized block experiment showed that there were no significant differences between the treatments (distance from tile lines). This is

not surprising when one considers the nature of the water table recession curves, which showed substantial drawdown only right over the tile lines, and the soil chemical profiles which showed salinity reductions mainly within the surface 30 cm.

The nature of the crop in 1978 was completely different. Even though the crop was seeded relatively late in the spring, the moist and warm soil allowed rapid and even germination. The regular and substantial rainfall which occurred throughout the growing season prevented the development of a crusting problem and promoted even growth of the crop. Crop stand counts for the same 40 sites as in 1977 yielded an average of 110 plants per square meter, a 43% increase over the previous year. Most of the plants were headed out by the last week of July and the crop appeared both lush and healthy. The mature crop was sampled and harvested in mid-September. Grain yield and total dry matter data for the 70 sites are presented in Tables B and C of Appendix 5. Analysis of variance of these data indicated that there was no significant effect of distance from tile lines on crop yield.

The improved crop yield was undoubtedly due to improved soil structure and initial moisture conditions. Regular precipitation received throughout the growing season also maintained an excellent moisture regime within the surface 30 cm which would effectively decrease the effects of salinity of that zone. The concept that plants obtain 40% of

their water requirements from the surface 30 cm (Ayers, 1977) plus the idea that in saline soils plants may take up even more water from the least saline zone (Ayers, 1977; Maas and Hoffman, 1977) may also be responsible for the increase in yields. Barley would be expected to grow reasonably well under these moderately saline conditions.

Van't Woudt and Hagan (1957) emphasize that the overriding influence of local conditions make individual reports of crop yield increases following drainage of little general value. This statement is particularly applicable to the climatic conditions encountered at the Magrath site during the study. Further study will indicate whether or not satisfactory yields can be maintained at this site.

V. SUMMARY AND CONCLUSIONS

Serious salinity problems in the Magrath Irrigation District and many other irrigated areas in southern Alberta have warranted appraisal of the effectiveness of shallow plastic drainage tubing in providing water table and salinity control. Many of the irrigated soils in southern Alberta are underlain by slowly permeable glacial till or lacustrine deposits at shallow depths. Thus, installation of drainage materials at depths of 2 m or more, as recommended for salinity control in most irrigated areas of the United States and elsewhere, is not practical. Lower evapotranspiration rates and a shorter growing season in southern Alberta, compared to the foregoing areas, theoretically do not induce as much upward movement of salt-laden groundwater from shallow water tables. Hence it was postulated that drainage tubing could be placed at shallower depths and still maintain a favorable salinity level in the root zone.

The performance of the grid drainage system at Magrath throughout the 1977 and 1978 growing seasons allowed appraisal of the ability of the system to provide water table and salinity control for improved crop yields. Shortly after installation of the drainage system the water table was lowered to depths corresponding to the depths of the

tile lines throughout the site. During irrigations the water table started to rise within 3 to 4 hours from the commencement of water application and reached a maximum level (about 30 cm from surface) as the final set was almost completed. Following irrigation the water table gradually receded to pre-irrigation levels within about 48 hours.

Water table recession curves were similar in shape for the 15 and 30 m spacings. Curves were generally quite flat with substantial drawdown occurring only directly over the tile lines. Recession times were well within the limits (3 to 4 days) defined for prevention of root damage caused by prolonged waterlogging. The response of the water table indicated that the grid drainage system was behaving as an interceptor-relief drain; therefore lateral spacings might be increased to 60 m or more and still achieve water table control. Research is necessary to verify such a proposal.

Discharge from the entire drainage system exhibited a pattern which was very similar to the water table fluctuations. Thus, the drainage system did not appear to be backed up for very long periods of time and the system disposed of water very rapidly.

Throughout 1977 and 1978 the range in water quality of drainage effluent remained rather constant from June to mid-September with EC values ranging from 5 to 8 mmhos/cm and SAR's from 7 to 10. A dilution effect of 1 or 2 EC or SAR units was detected during irrigation periods when large quantities of salts were removed by the drainage system.

The EC and SAR values of the soil profile were decreased significantly only for the 0 to 15 cm depth and sometimes for the 15 to 30 cm depth. Many of the profiles showed salt bulges at 30 to 60 cm, below which salinity remained constant. Proximity to tile lines (15 versus 30 m spacing) was not a significant factor in determining the observed changes in salinity. While capillary rise would be minimal at the site since the water table was maintained within the coarse layer, unsaturated flow would logically account for some upward resalinization.

Dramatic increases in crop yield were observed in 1978 as compared to the 1977 season. The crop stand was increased by 43% from 77 plants/m² in 1977 to 110 in 1978 and grain yield rose from 1310 kg/ha in 1977 to 3900 in 1978. Extremely uneven germination and emergence in 1977 may be attributed to the very dry moisture conditions into which the crop was seeded and to severe soil structure deterioration resulting from extensive land-forming operations. Crusting was also a severe problem after the first irrigation. Improved structure and moisture conditions at seeding time in 1978 prevented the development of a crusting problem and promoted the more even germination of the crop than in 1977. The distance of the crop samples from the tile lines did not have a statistically significant influence upon the results obtained. Continued study is needed to ensure that high yields can be maintained at the site.

Within the Magrath Irrigation District some 400 hectares adjacent to the study area have similar salinity and water table characteristics (Paterson et al., 1977). However, the rather unique nature of the soil profile within the experimental site, wherein a coarse layer is present at about the depth of the drains, makes extrapolation even to adjacent areas very difficult. The extreme difficulty in determining a representative K value for the soil material at the site also exemplifies the problems experienced when trying to apply drain spacing formulas in drainage design. Results indicated that drainage problems are site specific and require thorough investigation before drainage procedures can be recommended. Continued study of the Magrath site is needed to determine how the water table responds so rapidly during major applications of water and whether or not the experimental values of K reflect the actual water transmission properties of the upper soil. Other areas requiring continued monitoring to observe how reclamation is proceding are water quality, soil chemistry and crop yield.

Further research is also needed throughout southern Alberta to gain an appreciation for the behavior of drainage systems within the assortment of soil and surficial geological materials encountered.

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Appendix 1. Calculation of hydraulic conductivity by Hvorslev pump out method.

This method involves the rapid removal of a slug of water from a water table well or piezometer and the measurement of water level response over time. The ratio of head change (H/Ho) is then plotted logarithmically against time and the hydraulic conductivity is calculated as follows:

$$K = \frac{A}{F \times T}$$

Where: K = hydraulic conductivity, cm/sec.
A = crossectional area of the well or piezometer, cm^2.
F = a shape factor accounting for the geometry of the installation, cm.
T = basic time lag or the time it takes the logarithmic head change to reach H/Ho = 0.37.
Ho = equilibrium water level - water level following removal of slug.
H = equilibrium water level - water level at selected times during response.

The shape factor is calculated from:

$$F = \frac{2\pi L}{\ln\left[\frac{L}{D} + \sqrt{1 + \left(\frac{L}{D}\right)^2}\right]}$$

Where: L = length of piezometer tip or length of water table well below water table.
D = diameter of borehole.

F = 130 cm for a D of 10.2 cm (4 inches) when L = 45 cm.

Appendix 2. Soil moisture status at certain times during 1977 and 1978 .

Table A. Moisture content of samples taken 6 to 6.5 hours after end of second irrigation - July 2 and 3, 1977 .

Location along Border	Depth (cm)	Percent Moisture 5th Border	11th Border
South end	0-30	30	39
	30-60	32	36
Middle	0-30	31	35
	30-60	41	31
North end	0-30	36	41
	30-60	26	32

Table B. Moisture content of samples taken 3 days (July 6) after second irrigation - 1977 .

		Percent Moisture		
Location	Depth (cm)	Midpoint of 30 m Spacing	Over Tile Line	Midpoint of 15 m Spacing
11th border	0-30	27	28	31
	30-60	24	24	28
	60-90	19	23	25
8th border	0-30	28	27	22
	30-60	29	24	23
	60-90	23	25	24
5th border	0-30	31	23	29
	30-60	24	25	25
	60-90	22	28	23

Table C. Soil moisture status prior to a 33.5 mm rainfall (June 26); after the rainfall (July 4); after a 57 mm rainfall (July 21); and prior to the first irrigation (August 1) - 1978.

Grid Location	Depth (cm)	Texture	Percent Moisture			
			June 26	July 4	July 21	August 1
F-8 East	0-30	CL	17	20	22	14
	30-60	C	21	26	25	24
	60-90	SCL	22	21	22	20
E-8 West	0-30	C	19	31	34	21
	30-60	C	20	24	24	23
	60-90	C	23	23	23	23
C-8 East	0-30	C	25	32	33	25
	30-60	C	21	23	29	24
	60-90	C	19	24	23	23
B-8 West	0-30	C	19	29	29	27
	30-60	C	22	24	26	22
	60-90	C	21	26	28	25

Appendix 3. Calculation of flow in drainage tubing when a pressure head is induced during irrigation.

Flow in the mainline when a pressure head is present is similar to the flow in a venturi tube wherein flow before the weir in the tube is equal to flow behind the weir plus the hydraulic head:

$$\frac{V_2^2}{2g} = \frac{V_1^2}{2g} + H$$

or:

$$\frac{\left(\frac{Q}{A_2}\right)^2}{64.4} = \frac{\left(\frac{Q}{A_1}\right)^2}{64.4} + H$$

where H = hydraulic head
Q = flow
V_1, A_1 = crosssectional area and velocity prior to weir
V_2, A_2 = crossectional area and velocity at the weir

Rearranging these terms to isolate Q gives:

$$Q = \left[\frac{4.03\ H\ (16)\ (A_2)^2\ (\pi^2\ D^4)}{\pi^2\ D^4 - 16\ (A_2)^2}\right]^{1/2}$$

A head of 1.0 m which was experienced during maximum discharges yields an estimated Q of:

$$Q(\text{US gpm}) = [1330869.6\ (H)]^{1/2}$$
$$= 153 \text{ US gpm} = 127 \text{ imperial gpm} = 9.6 \text{ l/sec.}$$

This calculation is not completely valid due to several assumptions made in its derivation and inefficiency in the drainage system, but it does indicate the magnitude of the discharge which might be expected.

Appendix 4. Salt removed in drainage effluent and runoff versus salt added from irrigation water.

	Salt in water applied (tonnes)	Salt in runoff (tonnes)	Salt in effluent (tonnes)
1977:			
2nd irrigation	1670	570	8625
3rd irrigation	3040	1040	11975
4th irrigation	2700	925	12300
1978:			
1st irrigation	2940	25	9950

Calculations:

Source	EC (mmhos/cm)
Effluent	5
Runoff	0.37
Irrigation	0.27

ppm = 850 X EC mmhos/cm if water is in the range 0.1 to 5 mmhos/cm.

Appendix 5. Crop yield data and statistical analyses .

Table A. Grain yield for 70 crop samples taken in 1977.

Sample Location	Distance from Drains (meters) 15.24	11.43	7.62	3.81	0	3.81	7.62
	Grain Yield (g/m^2)						
F-8 East	119	129	120	122	37	177	100
F-8 West	175	265	206	50	190	20	70
E-8 East	98	133	201	193	123	95	146
E-8 West	126	104	32	66	85	108	100
D-8 East	100	175	95	131	126	113	154
D-8 West	126	158	216	180	111	44	49
C-8 East	117	53	104	113	102	147	106
C-8 West	99	173	204	97	197	136	180
*B-8 East	163	116	200	118	-	137	118
B-8 West	163	151	169	130	203	172	203

* This line deleted when applying statistics due to missing data point.

Average = 1,310 kg/ha.

Analysis of Variance - Randomized Block Experiment

Ho: There is no effect of distance from tile line on crop yield.

Source of Variation	DF	SS	MS	F	5%	1%
Replicates	8	34,920.86	4,365.11	-	-	-
Treatments	6	11,038.41	1,839.74	0.75	2.3	3.2
Error	48	117,815.59	2,454.49			
Total	62	163,774.86				

Conclusion: There is no significant difference in crop yield resulting from proximity to tile line.

Table B. Grain yield for 70 crop samples taken in 1978.

	Distance from Drains (meters)						
Sample Location	15.24	11.43	7.62	3.81	0	3.81	7.62
	Grain Yield (g/m^2)						
F-8 East	520	440	550	395	390	495	475
F-8 West	485	465	405	325	295	160	295
E-8 East	265	255	395	405	345	430	400
E-8 West	415	420	260	385	550	470	360
D-8 East	300	275	295	260	320	405	385
D-8 West	420	400	420	405	305	140	220
C-8 East	400	265	260	355	410	365	245
C-8 West	430	510	490	470	435	325	390
B-8 East	285	365	365	440	435	355	315
B-8 West	555	440	705	620	525	515	430

Average = 3,900 kg/ha.

Analysis of Variance - Randomized Block Experiment

Ho: There is no effect of distance from tile line on crop yield.

Source of Variation	DF	SS	MS	F	5%	1%
Replicates	9	329,235.71	36,581.74	-	-	-
Treatments	6	33,840	5,640	0.83	2.3	3.2
Error	54	368,074.29	6,816.19			
Total	69	731,150				

Conclusion: There is no significant difference in crop yield resulting from proximity to tile line.

Table C. Total dry matter of 70 crop samples taken in 1978.

Sample Location	Distance from Drains (meters) 15.24	11.43	7.62	3.81	0	3.81	7.62
	Total Dry Matter (g/m^2)						
F-8 East	925	835	985	680	685	880	825
F-8 West	845	820	740	605	545	380	480
E-8 East	480	500	625	715	590	715	695
E-8 West	755	820	500	700	985	895	660
D-8 East	600	510	550	490	550	700	690
D-8 West	815	805	860	795	635	365	460
C-8 East	760	490	485	665	725	620	440
C-8 West	945	1,020	1,010	915	850	640	750
B-8 East	600	690	710	885	825	735	680
B-8 West	1,070	895	1,215	1,120	990	925	820

Average - 7,310 kg/ha.

Analysis of Variance - Randomized Block Experiment

Ho: There is no effect of distance from tile line on crop yield.

Source of Variation	DF	SS	MS	F	5%	1%
Replicates	9	1,204,093.21	133,788	-	-	-
Treatments	6	131,337.14	21,889.52	1.18	2.3	3.2
Error	54	1,000,784.3	18,533.04			
Total	69	2,336,214.64				

Conclusion: There is no significant difference in crop yield resulting from proximity to tile line.